AD-A101 385 SOIL CONSERVATION SERVICE OXFORD MS SEDIMENTATION LAB F/G 8/8
STREAM CHANNEL STABILITY.(U)
APR 81 D G DECOURSEY

UNCLASSIFIED NL

1 OF 3
AD
A101385

LEVEL II

AD A101385

STREAM CHANNEL STABILITY

COMPREHENSIVE REPORT

Project Objectives 1 thru 5

by

D. G. DeCoursey

USDA Sedimentation Laboratory
Oxford, Mississippi

April 1981

Prepared for
US Army Corps of Engineers, Vicksburg District
Vicksburg, Mississippi

Under
Section 32 Program, Work Unit 7

(6)

STREAM CHANNEL STABILITY.

(9) COMPREHENSIVE REPORT,

Project Objectives 1 through 5

by

(10) D. G. DeCoursey 1/

USDA Sedimentation Laboratory
Oxford, Mississippi

(11) April 1981

(12) 237

Prepared for

US Army Corps of Engineers, Vicksburg District
Vicksburg, Mississippi

Under

Section 32 Program, Work Unit 7

1/ Hydraulic Engineer; Research Leader, Hydrology and Remote Sensing Unit and Director, USDA Sedimentation Laboratory, Oxford, MS.

EXECUTIVE SUMMARY

The Yazoo River Basin in Mississippi has been a source of problems for many decades, with excessive erosion and bank instability necessitating costly countermeasures both in the hill region and in the downstream Delta area. Hill streams are degrading, resulting in bank caving, land loss, and damage to highway bridges. Many streams have enlarged to the extent that 50 to 100-year runoff events are contained within banks. Downstream aggradation is caused by the lower channel slopes that exist in the Delta. It results in more frequent flooding and loss of navigation. The demonstration project, Work Unit 7, is directed toward determining the causes of stream channel instability in the Yazoo Basin, whether chronic or acute, and toward developing ways to work best with natural controls to develop the least expensive program to re-establish drainage basin stability. A wide variety of bed and bank stability measures are being tested to determine the most economical and effective means of providing the needed protection.

The research program; conducted under Reimbursable Agreement with the Vicksburg District, Corps of Engineers, at the USDA Sedimentation Laboratory; was initiated to gain better knowledge of channel stability problems and of improved methods for channel stabilization. The need for this program is emphasized by the extremely complex combination of events, site conditions and land-use changes that have been responsible for channel stability problems that exist in the Yazoo River Basin. The complexity of the processes functioning in the basin and the significant influence that the condition of the watershed upstream has on channel stability, indicates that the most feasible approach to the solution of channel stability problems would combine upland conservation management practices with channel stability design on a watershed basis. This approach has the added benefit that it would maintain or enhance crop productivity of the upland areas.

The Laboratory's research program encompasses studies of both watershed management practices and channel protection activities. Channel stabilization devices have been constructed on bluff-line tributaries of the Yazoo River for observation. The Goodwin Creek Watershed was instrumented to evaluate the influence of upstream watershed conditions on channel stability. The field studies were supported by laboratory studies

of flow resistance, turbulence and sediment transport. Several hydrologic models were developed to aid in interpretation of data and assessment of remedial activities.

The research program had five major objectives:

1. Determining the influence of grade control structures on channel stability,
2. Monitoring the performance of selected channel stabilization methods,
3. Evaluating the effects of geology, geomorphology, soils, land use, and climate on runoff and sediment production from major source areas,
4. Estimating the water and sediment production from a large, mixed-land-use watershed and the integrated effects on channel stability,
5. Evaluating the relation between valley stratigraphy and channel morphology and their combined effects on channel stability.

These five research objectives were addressed in several overlapping projects. Reports of these projects are presented in the Appendices to this report. This comprehensive report on the study of channel stability problems in the Yazoo Basin is presented to demonstrate an approach used in making an assessment of channel stability.

Chapters 2 thru 7 are materials that provide the reader with general information of the type needed to make assessments of channel stability. Chapter 8 is a description of Goodwin Creek and an assessment of channel stability in Goodwin Creek watershed. The material presented in the chapters is as follows:

Chapter 2, River Characteristics and Morphology, provides a summary of major topics in channel morphology. The transport processes responsible for the movement of channel bed material and the bed forms that characterize alluvial channels in both the upper and lower flow regimes are described. Channel roughness, composed of grain, bed form and plan form elements is described as a dynamic system. The turbulence forces responsible for entrainment of sediment particles are described. Physical characteristics of material that normally make up the bed and banks of stream systems are also described. Areas of excessive erosion and deposition in bendways are discussed. The characteristics of straight,

sinuous, meandering, or braided alluvial channels and how they relate to sediment transport rates, channel slope, and discharge are described. The last section of the chapter describes various geomorphic relations of channel size, shape, and sinuosity.

Chapter 3, which pertains to the impact of watershed processes on the channel system, describes the effect of land use management practices in the upland watershed on volumes of runoff and sediment production. Sources of sediment production and man's influence on these sources of sediment are discussed. Changes in the climate of a region as they influence runoff and sediment yield are also discussed.

Chapter 4 describes processes leading to channel instability and erosion. Included are discussions of fluvial entrainment of bed and bank materials, particle segregation and armoring, the erosion of cohesive materials, weathering of surface materials, processes responsible for sloughing and massive bank failure, liquefaction of silty and sandy soil, and erosion of bank materials caused by seepage and wave action. The latter part of the chapter describes geomorphic processes or mechanisms of channel erosion. These processes include changes in flow rate, sediment load, and channel slope. The effect that these changes have on channel stability are described.

Chapter 5 discusses the many methods of channel protection with emphasis on the use of grade control and vegetation as the two most cost-effective measures. Also described are armor, retards, dikes or jetties, bulkheads, and baffles.

Chapter 6 identifies the processes active in a given situation and evaluates effectiveness of specific problem solutions. It was written to aid individuals in solution of specific site problems. The concepts of channel system instability, channel reach instability, and channel cross-section or point instability, are discussed in depth. An approach to such a study describes the necessary material to be collected, sources of useable data, and use of mathematical models or other procedures for use in assessment. Four major causes of channel system instability (land use change, climatic change, downstream control, and excedence of a threshold of stability) are described using historic information, the application of geomorphic relations, and hydrologic models. Alternatives to solution of stability problems include "living with the existing channel system" if its

equilibrium size has already been reached and use of grade control in conjunction with upland watershed treatment measures. Channel reach and channel point instability are discussed in less detail.

Chapter 7 is a brief discussion of some of the mathematical models that have been developed or are under development for possible use in studying channel stability. The first part of the Chapter describes how some of these models are applied to streambank stability problems. The stability of non-cohesive, cohesive and composite banks are discussed. The effect of tensile cracks, which are prevalent in many high, steep banks is included in the discussion. Three hydrologic-type models are described. They are a single event model, a continuous simulation model, and a quasi 3-dimensional finite element model. The single event model is physically-based and was developed because the bulk of the sediment moves during a few large storm events. Interception, infiltration, overland and channel water routing, overland sediment routing, channel sediment routing and input data requirements are discussed. The proposed continuous simulation model is easier to use and requires less input data. Routing of water and sediment from the model is accomplished using the channel component of the single event model. Procedures used to estimate the volume of surface runoff, percolation, return flow, evapotranspiration, water balance in reservoirs, sediment yield and input data requirements are discussed. The quasi 3-dimensional finite element model discussed was developed to analyze sediment movement at specific sites in a stream channel; for example, at the confluence of two channels or in the vicinity of various stabilization structures such as those presented in Chapter 5. This model is not yet operational, but the potential for its full development is good enough that the concepts are presented.

Chapter 8 is an assessment of channel stability problems in Goodwin and Johnson Creek Watersheds and a description of the research facilities placed in operation in the Goodwin Creek Watershed. The Chapter includes a description of the watersheds, including criteria for their selection as a research facility.

Chapter 9 contains the Summary, Conclusions, and Recommendations. The Summary is nearly the same as this Executive Summary. The Conclusions and Recommendations are presented in the order of the five Research Program Objectives. The summarized material is presented in detail in the 14

Appendices. To avoid presenting a confusing picture, the recommendations immediately follow the conclusions for each of the five objectives. Only in the discussion of Research Objective 4 is the above pattern not followed. Since Objective 4 is primarily the development of mathematical models that can be used to estimate runoff and sediment yield, it consists of rather independent sets of material. In this case, the recommendations follow the conclusions for each project.

This Comprehensive Report on Channel Stability was written to describe how to carry out an analysis of a channel stability problem. Therefore it is rather general; only the last chapters describe problems of channel stability in the Yazoo River Basin. Detailed reports of the various research projects associated with ~~our~~ study of channel stability problems in the Yazoo River Basin are presented as Appendices. They are completely independent reports, and need no introductory material. In total they address all five project objectives included in the Reimbursable Agreement between the Vicksburg District of the US Army Corps of Engineers and the USDA Sedimentation Laboratory.

Table of Contents

List of Tables

List of Figures

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) AND
METRIC (SI) TO U.S. CUSTOMARY UNITS OF MEASUREMENT1/

Units of measurement used in this report can be converted as follows:

To convert	To	Multiply by
mils (mil)	micron (μm)	25.4
inches (in)	millimeters (mm)	25.4
feet (ft)	meters (m)	0.305
yards (yd)	meters (m)	0.914
miles (miles)	kilometers (km)	1.61
inches per hour (in/hr)	millimeters per hour (mm/hr)	25.4
feet per second (ft/sec)	meters per second (m/sec)	0.305
square inches (sq in)	square millimeters (mm^2)	645.
square feet (sq ft)	square meters (m^2)	0.093
square yards (sq yd)	square meters (m^2)	0.836
square miles (sq miles)	square kilometers (km^2)	2.59
acres (acre)	hectares (ha)	0.405
acres (acre)	square meters (m^2)	4,050.
cubic inches (cu in)	cubic millimeters (mm^3)	16,400.
cubic feet (cu ft)	cubic meters (m^3)	0.0283
cubic yards (cu yd)	cubic meters (m^3)	0.765
cubic feet per second (cfs)	cubic meters per second (cms)	0.0283
pounds (lb) mass	grams (g)	454.
pounds (lb) mass	kilograms (kg)	0.453
tons (ton) mass	kilograms (kg)	907.
pounds force (lbf)	newtons (N)	4.45
kilogram force (kgf)	newtons (N)	9.81
foot pound force (ft lbf)	joules (J)	1.36
pounds force per square foot (psf)	pascals (Pa)	47.9
pounds force per square inch (psi)	kilopascals (kPa)	6.89
pounds mass per square foot (lb/sq ft)	kilograms per square meter (kg/m^2)	4.88
U.S. gallons (gal)	liters (L)	3.79
quart (qt)	liters (L)	0.946
acre-feet (acre-ft)	cubic meters (m^3)	1,230.
degrees (angular)	radians (rad)	0.0175
degrees Fahrenheit (F)	degrees Celsius (C)2/	0.555

2/ To obtain Celsius (C) readings from Fahrenheit (F) readings, use the following formula: C = 0.555 (F-32).

Metric (SI) to U.S. Customary

To convert	To	Multiply by
micron (μm)	mils (mil)	0.0394
millimeters (mm)	inches (in)	0.0394
meters (m)	feet (ft)	3.28
meters (m)	yards (yd)	1.09
kilometers (km)	miles (miles)	0.621
millimeters per hour (mm/hr)	inches per hour (in/hr)	0.0394
meters per second (m/sec)	feet per second (ft/sec)	3.28
square millimeters (mm^2)	square inches (sq in)	0.00155
square meters (m^2)	square feet (sq ft)	10.8
square meters (m^2)	square yards (sq yd)	1.20
square kilometers (km^2)	square miles (sq miles)	0.386
hectares (ha)	acres (acre)	2.47
square meters (m^2)	acres (acre)	0.000247
cubic millimeters (mm^3)	cubic inches (cu in)	0.0000610
cubic meters (m^3)	cubic feet (cu ft)	35.3
cubic meters (m^3)	cubic yards (cu yd)	1.31
cubic meters per second (cms)	cubic feet per second (cfs)	35.3
grams (g)	pounds (lb) mass	0.00220
kilograms (kg)	pounds (lb) mass	2.20
kilograms (kg)	tons (ton) mass	0.00110
newtons (N)	pounds force (lbf)	0.225
newtons (N)	kilogram force (kgf)	0.102
joules (J)	foot pound force (ft lbf)	0.738
pascals (Pa)	pounds force per square foot (psf)	0.0209
kilopascals (kPa)	pounds force per square inch (psi)	0.145
kilograms per square meter (kg/m^2)	pounds mass per square foot lb/sq ft)	0.205
liters (L)	U.S. gallons (gal)	0.264
liters (L)	quart (qt)	1.06
cubic meters (m^3)	acre-feet (acre-ft)	0.000811
radians (rad)	degrees (angular)	57.3
degrees Celsius (C)	degrees Fahrenheit (F)[3/]	1.8

1/ All conversion factors to three significant digits.

3/ To obtain Fahrenheit (F) readings from Celsius (C) readings, use the following formula: $F = 1.8C + 32$.

Notation

a Major axis of a particle, coefficients

b Major axis of a particle, coefficients, channel bottom width, width of soil slab to tensile crack

C Chezy' coefficient of flow resistance

C_1 Form coefficient (for spherical particles this is equal to $\pi/6$), lift coefficient

C_2 Form coefficient for effective surface area of a particle

C_3 Form coefficient related to the effective surface area of a particle in the direction of the force

c Minor axis of a particle, coefficients, soil cohesion

c_b Coefficient

c_d Coefficient

D Depth of flow

d Channel depth, mean depth, grain size

d_{ga} Geometric mean diameter of armored sediment mixture

d_{go} Geometric mean diameter of original sediment mixture

d_s Characteristics diameter of a particle

d_{95} Particle size, 95% of which is finer than this size

ET Evapotranspiration

EV Evaporation from the water surface of a reservoir

F Width depth ratio b/d

F_1 The resulting force on a bank particle in flowing water, active force causing planar failure

F_2 Shear resistance along planar failure surface, the restoring force on a bank particle in flowing water

F_s Factor of safety in bank slope stability

f Darch-Weisbach Friction coefficient

G_s Suspended load transport rate

g Acceleration of gravity

$\bar{g}$ Mean probability for armor coat grains to stay

H Height of the bank slope, amount of physical drop in grade control structure

H_c Critical bank height

i Bank slope angle

k_b Coefficient

k_d Coefficient

L Length of bank failure surface

M Percentage of silt and clay in the perimeter of stream channels

N Sum of forces normal to bank failure surface

N_s Taylor stability number

n Mannings' coefficient of flow resistance, Mannings' n

n' Roughness parameters of Manning type

O Percolation below root zone

P Channel sinuosity, ratio of channel length to valley length

p Precipitation

p(d) Probability of grain size d not being removed

P_o Density function of the grain size distribution of sediment mixture

Q Flow rate or volume of water, discharge

Q_b Percentage of total sediment load that is bed load

QI Inflow during the period of a day

QM Mean annual discharge

QO Outflow during the period of a day

QR Return flow within a given time period

Q_s Sediment discharge

R Radius of channel curvature at mid stream

S_a Sum of active forces along failure surface

S_b Channel bed slope

S_f Energy gradient

SM Soil moisture content at beginning of a period

SM_t Soil moisture content at end of a period of t days

SP Seepage from a reservoir

S_p Particle shape factor

S_r Shear resistance along failure surface

s Slope or gradient

t Time

U Flow velocity or the velocity of flow near a particle

U_* Shear velocity

u Internal pore water pressure

u_{*c} Critical shear velocity

V Velocity of the water or sediment particles, mean velocity

VM Volumes of water stored in all reservoirs within a subwatershed at end of day

VM_o Volume of water stored in all reservoirs within a subwatershed at beginning of the day

W Weight of bank material above failure surface

W_s Submerged weight of a particle

w Width of channel at top of bank, channel width

x Distance down the channel

y Flow depth

y_c Critical depth

Z_p Vertical depth to failure plane

z Depth of tension crack

z_o Depth of tensile stress

α Limiting bank slope when subject to internal pore water pressure

γ Bulk weight of the bank material, specific weight of water

γ_s Specific weight of sediment particle

θ The bank angle

λ Stream meander wave length, the flow angle of water on a bank particle

ν Kinematic viscosity

ρ The bulk density of water or water sediment mixture

σ Standard deviation or gradation coefficient of particle sizes

σ_{go} Geometric standard deviation of original mixture

τ_c Critical shear stress

τ_o Bed shear stress

ϕ The angle of repose, drained

ϕ' Angle of repose in saturated state

ψ_* Einstein's bed load parameter

1 INTRODUCTION

Stream channels as we see them today, whether they be the small upstream tributaries or the main channel at a downstream point, are the result of numerous cycles of erosion and deposition that have taken place over long periods of time. These cycles of erosion and deposition gradually change the landscape, but this change is not a steady one. Cyclic fluctuations in climate lead to changes in the land cover and to extreme variability in rates of erosion and transport. The net result is a cyclic pattern of degradation and aggradation of valleys and stream channels. Thus, in a given drainage system we find an area or zone that is producing sediment; this can be either the land surface adjacent to the channel or the stream channel itself. We also find a reach of the drainage system that is acting primarily as a transporter of the material being supplied. If we go downstream far enough, we find a zone of deposition. The size of the contributing zone, the length of the transporting zone, and the extent of the deposition zone change in response to changes in climate, land cover, the quantity and size of material being removed and the continually changing hydraulic characteristics of the stream channel. Thus the drainage system is dynamic, always adjusting to the external conditions imposed upon it.

At times in these cyclic patterns of aggradation and degradation, thresholds are exceeded and major changes take place in the configuration of the valley or stream channel. This leads to rejuvenation of the tributaries and to a major change in the character of the entire stream system. The forces that lead to excedence of thresholds have been described by Schumm (1973) as extrinsic or intrinsic in character. Extrinsic forces are those that depend upon an external influence; for example, changes in the land use or climate that impose different stresses on the channel system. Intrinsic forces are associated with changes in the character of materials in the bank or bed of a channel; for example, the changes in strength of the various strata at a site due to weathering or seepage forces. The thresholds that appear to be exceeded can develop as a result of gradual changes in the state of the system, as geomorphic changes evolve over time; or they can be explosive, occurring over very short periods of time. A progressive increase in channel sinuosity, which is

typical of many river systems, can lead to natural channel cutoffs or avulsive channel straightening. This is an example of progressive excedence of a geomorphic threshold. Massive channel erosion resulting from an extreme flood flow can lead to irreversible channel deterioration. This is an example of an explosive excedence of a geomorphic threshold.

Streams and channels throughout the Country are displaying channel changes associated with both types of threshold excedence. The U.S. Army Corps of Engineers (1978) estimates that there are 142,000 miles of serious erosion of the banks of stream channels in the United States and 575,000 miles of less severe erosion resulting in annual losses of $270 million. The estimated annual costs of protection are $870 million. Thus, there is an obvious need to find less costly methods of protection and prevention.

1.1 THE SECTION 32 PROGRAM

The magnitude of economic losses associated with streambank erosion caused the Congress of the United States to pass the River and Harbor Act of 1968. Title 1, Section 120 of this Act (Public Law 90-483) directed the Corps of Engineers to "make studies of the nature and scope of damages which result from streambank erosion throughout the United States...." The ensuing Report (U.S. Army Corps of Engineers, 1969) appraised annual damages at approximately $90 million and annual cost of conventional bank protection required to prevent damage at about $420 million. The Report concluded that "...a substantial research program is needed to develop cheaper and more effective methods of treatment. Such a program should also include efforts to improve our understanding of the mechanics of stream channel behavior and bank erosion...."

As a result of the Report, the River and Harbor Act of 1968 was followed by the Streambank Erosion Control Evaluation and Demonstration Act of 1974 (Section 32, Public Law 93-251) Amended by Public Law 94-587, Sections 155 and 161. This Legislation authorized a five-year program consisting of an updated analysis of the extent and seriousness of streambank erosion, research studies of soil stability and hydraulic processes to identify causes of erosion, an evaluation of existing bank protection techniques, and construction and monitoring of demonstration projects to evaluate the most promising bank protection methods and techniques.

To accomplish the objectives of the authorizing legislation, a steering committee developed a program consisting of the following work units:

1. Evaluation of extent of streambank erosion, nationwide.
2. Literature survey and evaluation of bank protection methods.
3. Hydraulic research on effectiveness of bank protection methods.
4. Research on soil stability and identification of causes of streambank erosion.
5. Ohio River demonstration projects.
6. Missouri River demonstration projects.
7. Yazoo River Basin demonstration projects.
8. Demonstration projects on other streams, nationwide.
9. Reconstruction at demonstration projects.
10. Reports to Congress.

Status of the programs in each of the work units was reported in an Interim Report to Congress in September 1978 (see U.S. Army Corps of Engineers, 1978). This Report was used to estimate the losses associated with streambank erosion and costs of protection quoted in the Introduction. The figures are updated estimates of those from the 1969 study, and show nearly a 100 percent increase between 1969 and 1978.

The material presented in this Report and the Appendix Chapters is part of Work Unit No. 7, the Yazoo River Basin demonstration project. However, we will be reporting on channel stabilization methods which relate to Work Unit No. 2 and on the identification of causes of streambank erosion which related to Work Unit No. 4.

The Yazoo River Basin of Mississippi has been a source of problems for many decades, with excessive erosion and bank instability necessitating costly counter measures both in the hills and in the downstream Delta area. Hill streams are degrading, resulting in land loss, bank caving, and damage to highway bridges. Many streams have enlarged to the extent that 50 to 100 year runoff events are contained within banks. Aggradation downstream is caused by lower channel slopes in the Delta. This results in flooding and loss of navigation. The demonstration project, Work Unit No. 2 is directed toward determining the causes of stream instability, whether chronic or acute, and toward determining ways to best work with natural controls, so as to develop the least expensive program to re-establish

drainage basin stability. A wide variety of bed and bank stability measures are being tested to determine the most economical and effective means of providing the needed protection.

1.2 THE USDA SEDIMENTATION LABORATORY RESEARCH PROGRAM

In support of the Yazoo River Basin Demonstration Projects, the USDA Sedimentation Laboratory initiated a research program, within the Yazoo River Basin, to gain better knowledge of channel stability problems and improved methods of channel stabilization. The need for this program is emphasized by the extremely complex combination of events, site conditions and land use changes that have been responsible for the channel stability problems that exist in the Yazoo River Basin.

The Yazoo River, a tributary of the Lower Mississippi River, flows through the Mississippi Delta, one of the most highly productive agricultural areas in the country. Because this area has been subject to periodic flooding, the Corps of Engineers and other action agencies have completed extensive flood prevention projects. These consist of levees, channel improvements, land use management, and flood control reservoirs. Four major reservoirs (Arkabutla, Sardis, Enid, and Grenada) have been placed on major tributaries to the Yazoo for flood control. Even though they remove tremendous quantities of sediment from the Yazoo, deposition continues to be a problem in main channels of the Basin. Sediment accumulations are creating two major problems in the Yazoo River; (i) decreased carrying capacity and (ii) hazards to barge and ship traffic. Most of the sediment creating these problems is coming from numerous tributaries that flow into the flat Delta from the bluff line to the East. Some of this sediment originates in the channel beds and banks of these streams. Sediment from tributaries above the four major reservoirs is trapped in them and is not a problem as far as the Delta is concerned.

The base level control of these bluff line streams is the elevation of the Mississippi River. This elevation has not been constant during recent geologic history, but has fluctuated between glacial lows and inter-glacial highs and within smaller limits, the base elevation fluctuates seasonally. The magnitude of the relief change is not known. Fisk (1944) states the Mississippi Valley was entrenched 400 to 450 ft below present sea level during late Wisconsin glaciation (app. 250 ft entrenchment for the north Mississippi Delta). Saucier (1974), on the other hand, states that the

sand and gravel deposits in the Mississippi Valley may actually be preglacial. In either case the fluctuations of the ancestral Mississippi River should also be reflected in the valley deposits of the bluff line streams. The continuity of sequences of bluff line valley deposits serve as a useful bench-mark in relating the findings from this area to other areas of similar nature. Also, better definitions of the bluff line valley deposit sequences will aid in a better understanding of the history of the Mississippi Valley itself.

Land use practices have drastically affected all the watersheds[1] in the bluff line. Many watershed bottom lands have as much as 12 feet of recent (post-settlement) alluvium deposited over presettlement soils or remnants thereof. The properties of these old soils are pertinent with respect to channel stability.

Land use by man has increased the runoff in many areas. Channelization for flood abatement has accentuated the erosive channel flows by steepening the channels, containing proportionately more of the total flow within them, increasing the frequency of flows of a given magnitude, and reducing the extent of overbank flooding. This activity increases the sediment load and the ability of upstream channels to carry it. Ponds and small flood control structures trap large quantities of sediment that would normally be satisfying the sediment carrying capacity of the channel system. Degradation initiated by these sediment deficiencies has often moved upstream, producing a new cycle of upland dissection or channel rejuvenation. All of these activities and the geomorphological features of the channels affect channel stability directly. The geomorphological features were inherited from past conditions and may not reflect present conditions.

Upland land use and management practices influence the rate and amount of surface runoff, the rate and amount of sediment delivered to streams from the upland, and the physical and chemical characteristics of the produced sediment. These variables are prime determinates of the erosiveness of subsequent channel flow.

---

1 Throughout this Report the terms watersheds and catchments are used synonymously to mean that area of land draining in to a stream channel above any given point.

The complexity of the problem and the significant influence that the watershed upstream has on channel stability indicates that the most feasible approach to solution of channel stability problems includes both upland management practices and channel protection activities. Channel protective devices include grade control, fences, dikes, riprap, etc. The upland management practices are those which influence the rate and amount of runoff, the rate and amount of sediment production and those which affect the size and type of sediment produced. In general, these practices include maximized vegetative cover; conservation tillage practices, control of soil surface sealing and/or restricted internal drainage; land reshaping for erosion control; runoff management practices; and many others. A great advantage of this approach to solving channel stability problems, is that upland conservation management would be combined with channel stability design on a watershed basis. This would also maintain or enhance the crop productivity of the upland areas.

The research program of the USDA Sedimentation Laboratory encompasses study of both watershed management practices and channel protection activities. Various channel stabilization devices have been constructed on several bluff line tributaries of the Yazoo River for observation. Goodwin Creek, within the Peters Creek drainage basin, was instrumented to evaluate the influence of upstream watershed conditions on channel stability.

Basically, the project investigates the nature of (i) the channel and flow conditions in the vicinity of major channel stabilization devices, (ii) the geomorphological features of the study area, and (iii) watershed features including water and sediment source areas; as a basis for assessing their influence on channel stability. The channel and flow conditions are characterized by determining stream discharge, sediment load, groundwater conditions and channel shape. The geomorphological features are characterized by studying the channel morphology, watershed topography and valley stratigraphy. The watershed features are characterized by collecting data on major climatic, hydrologic, soil, land use, and sediment parameters. Modeling of channel stability is supported by laboratory studies of flow resistance, turbulent entrainment, and sediment transport.

The research program has five major objectives:

1. Determine the influence of grade control structures on channel stability.

2. Monitor the performance of selected channel stabilization methods.
3. Evaluate the effects of geology, geomorphology, soils, land use, and climate on runoff and sediment production from major source areas.
4. Estimate the water and sediment production from a large mixed land use watershed and the integrated effects on channel stability.
5. Evaluate the relation between valley stratigraphy and channel morphology and their combined effects on channel stability.

The balance of this Report summarizes the results of the reseach program at this time. However, the material is presented in a way that will, it is hoped, enable potential users to incorporate the findings in their own work. Thus, material describing river characteristics, channel morphology, sediment sources and impacts, channel stability and erosional processes and related information are presented as an introduction to the main discussions of channel stability. Detailed discussions of the fourteen individual studies supporting the research program are presented as "stand alone" Appendices.

2 RIVER CHARACTERISTICS AND MORPHOLOGY

Characteristics of a river or stream channel are the result of interaction of water and sediment input from the watershed upstream, composition of the bed and bank material, and any instabilities that may be present in the channel or watershed system. If there are no observable sediment accumulations or instabilities, then the physical characteristics of the channel are likely to be in dynamic equilibrium with the forces imposed by water and sediment inputs. However, if there are sediment accumulations or instabilities within the system, then the physical characteristics may not be in balance with the water and sediment induced forces.

Simons (1979) lists some of the most important features influencing the geometry of river channels. They are: velocity of the water, depth of water, slope of the energy grade line, density of the water sediment mixture, apparent dynamic viscosity of the water-sediment mixture, the gravitational constant, representative fall diameter of the bed material, the size distribution of the bed material, the concentration of bed-material discharge, the density of the sediment particles, the shape factor of the sediment particles, a shape factor for the reach of the stream, a shape factor for the cross section of the stream, and the seepage force in the bed of the stream. For a discussion of most of these terms see Simons and Richardson (1962) and Simons and Sentürk (1976). Those of special interest are discussed in the next few paragraphs.

2.1 BED CONFIGURATION

In sand and gravel bed streams, two major features of the channel bed are often confused even though there may be an order of magnitude difference in their size. The smaller features are dunes and similar bed forms; the larger features are sand or gravel bars. The mechanism of fluid force on the bed form in question, the mechanism of propagation of the bed form, and the mechanism of sediment movement and reworking through the bed configuration, are identical in both dune and bars. However, bars are generally defined as bed forms having lengths of about the same order as the channel width or greater. The biggest difference between bars and dunes is the residence time of particles. In bars it is much longer than that of particles in dunes. The lengths and widths of the bars depend upon the channel slope, the size gradation of the bed material and the average

flow and sediment concentrations. There are several types of bars depending upon their location in a stream channel. Along nearly straight uniform channels, bars will form alternately along the channel forcing the low flow and main thread of the water to take a sinuous path. Quite frequently the deepest water, a pool in low flow, is located opposite the alternate bar. The shallowest flow, a riffle, is located at the crossing between alternate bars. Depending upon the location of bends and tributary junctions, alternate bars can occur as isolated bars and some times as islands or middle bars. Many alluvial channels have transverse bars that generally extend diagonally from one bank to the other. Alternate and transverse bars move slowly downstream. However, their general configuration and relation to the dominant discharge is not well understood. For one thing most observations of bars are made at low flow. It may well be that what is observed at low flow as alternate bars may be transverse bars at higher flows. Figure 1 illustrates the main features of sand and gravel bars in a stream channel.

At major bends where flow separation tends to occur, point bars will develop on the inside. The size and shape of the bar will vary with flow conditions, but they do not move significantly relative to the bends. Bars also tend to develop at the mouth of tributaries. These tributary bars tend to have a long gentle upstream slope with a short downstream slope approximately equal to the angle of repose of the bed material.

The smaller bed forms, discussed below, tend to migrate downstream among the bars and are often seen covering the upstream slopes of bars. For additional information on bar formation, see Costello (1974), Wolman and Leopold (1957), Leopold and Wolman (1957), Wolman and Brush (1961) and Langbein and Leopold (1966). The International Workshop, sponsored by East Anglia University, on Engineering Problems in the Management of Gravel-Bed Rivers held in Newtown, Wales, U.K., June 23-28, 1980 included a large number of papers that discuss bar formation.

Dunes and other small scale forms of bed roughness are classified by flow regimes. In the lower or subcritical flow regime, the bed forms are ripples and dunes or ripples on dunes. In the upper or supercritical flow regimes they are plane bed, antidune standing waves, breaking antidune waves and chute and pool. Figure 2 shows the various bed forms in both the lower and upper flow regimes.

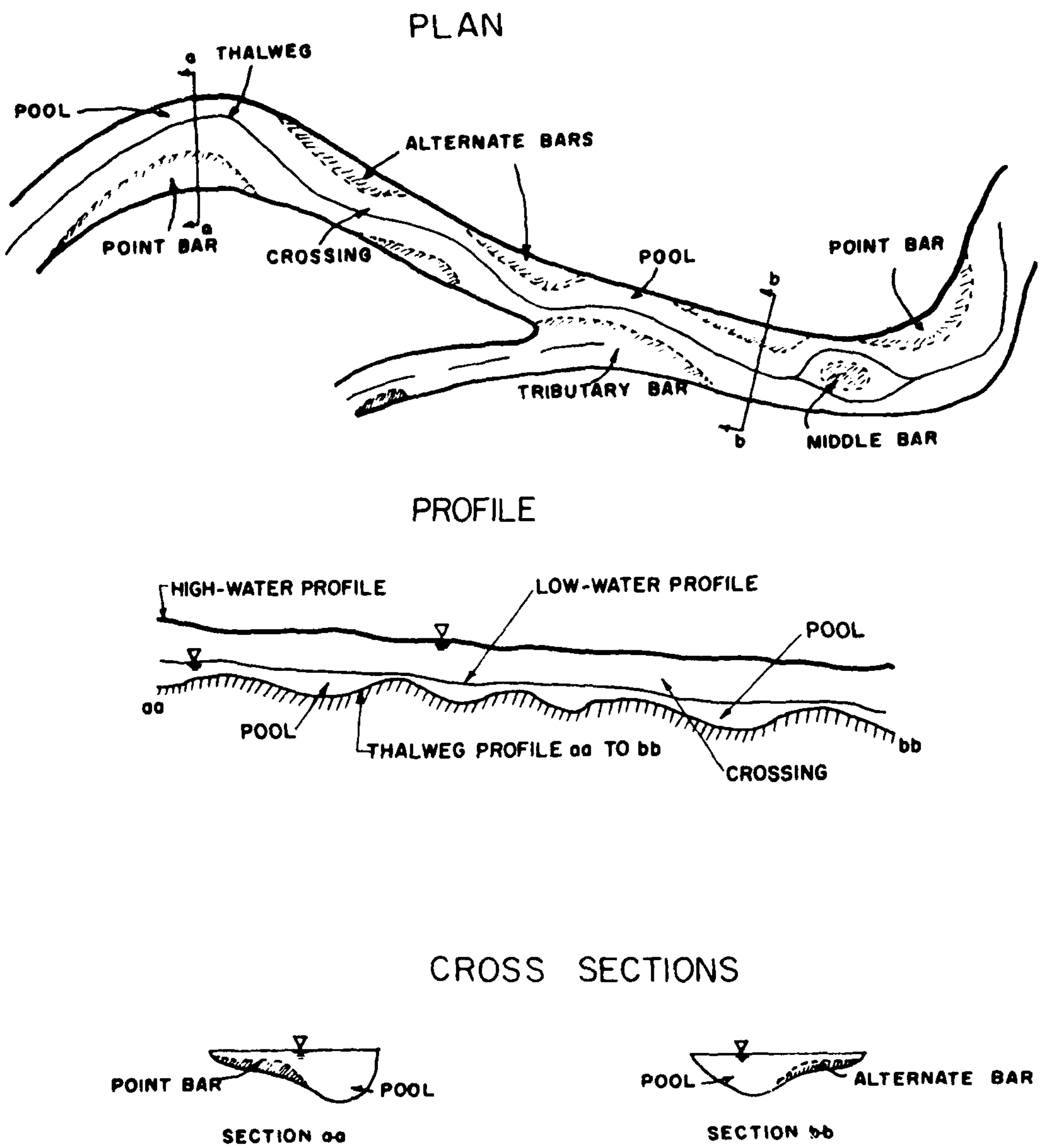


Figure 1 Configuration of bars

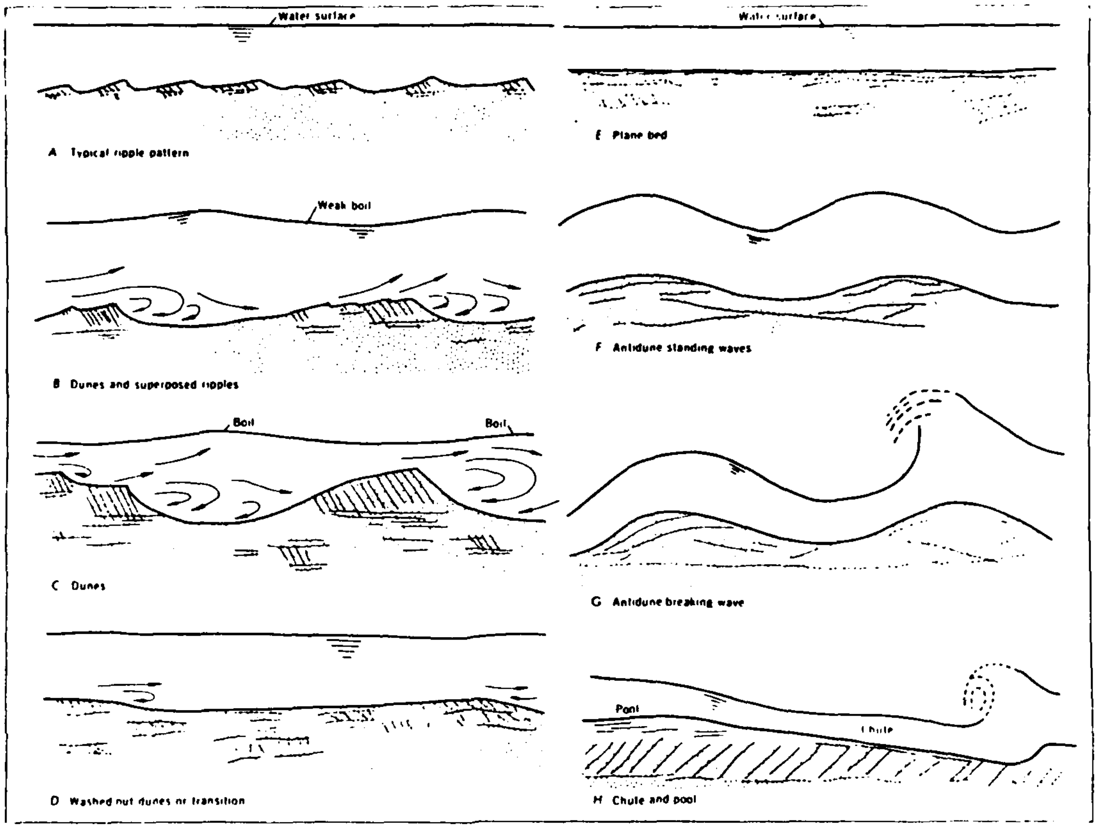


Figure 2 Forms of bed roughness in an alluvial channel

Ripples are very small bed forms that produce minimum form roughness. Dunes are bed forms larger than ripples. The length of dunes can be approximated by observing the spacing of water surface boils. Their length varies from a few feet in small streams to several hundred feet in the Mississipp River and their height from a few centimeters to 40 or 50 feet in the Mississippi River. Dunes are approximately triangular in shape with a gentle upstream slope and downstream slopes of 40° - 48°. Dunes reach a maximum height that is directly proportional to the shear stress or stream power and, within limits, the bed material size. Resistance to flow over dunes is quite high due primarily to form roughness.

In the lower flow regime bed material is transported downstream by a combination of two processes. In one of the processes, material from the back of the dune downstream of an advancing dune is eroded by reverse rollers and deposited on the face of the advancing dune. The reverse roller in the wake of the advancing dune deposits material at an angle slightly steeper than the angle of repose of the material. It also tends to deposit the coarser material at the base of the dune, and sweep the smaller particles toward the crest. This process is shown in Figure 3.

The other form of bed material transport is shown in Figure 4. In this process, material is swept up the back of a dune and avalanches down the face thus advancing the dune in a downstream direction. Bed forms move by a combination of both processes, the dominant process is determined by the bed material size distribution and velocity of flow. The velocity of the bed form movement is not constant and is obviously much lower than the velocity of the water. Also, bed forms do not move at a uniform or constant rate. One bed form can advance until it overtakes the one downstream resulting in formation of a dune with a higher amplitude.

In the upper flow regime there is a plane bed or there are standing waves and antidunes. However, starting with a dune bed situation, increasing the shear stress or stream power will also increase the amplitude of dunes to a critical value where they will be at their maximum height. As the shear stress continues to increase the dunes will be swept out and a flat bed will result. The velocities increase considerably as form roughness becomes small. Transport rates of the bed material become large.

When the shear stress or the stream power is increased beyond that which maintains a plane bed, water and sand waves gradually develop in the

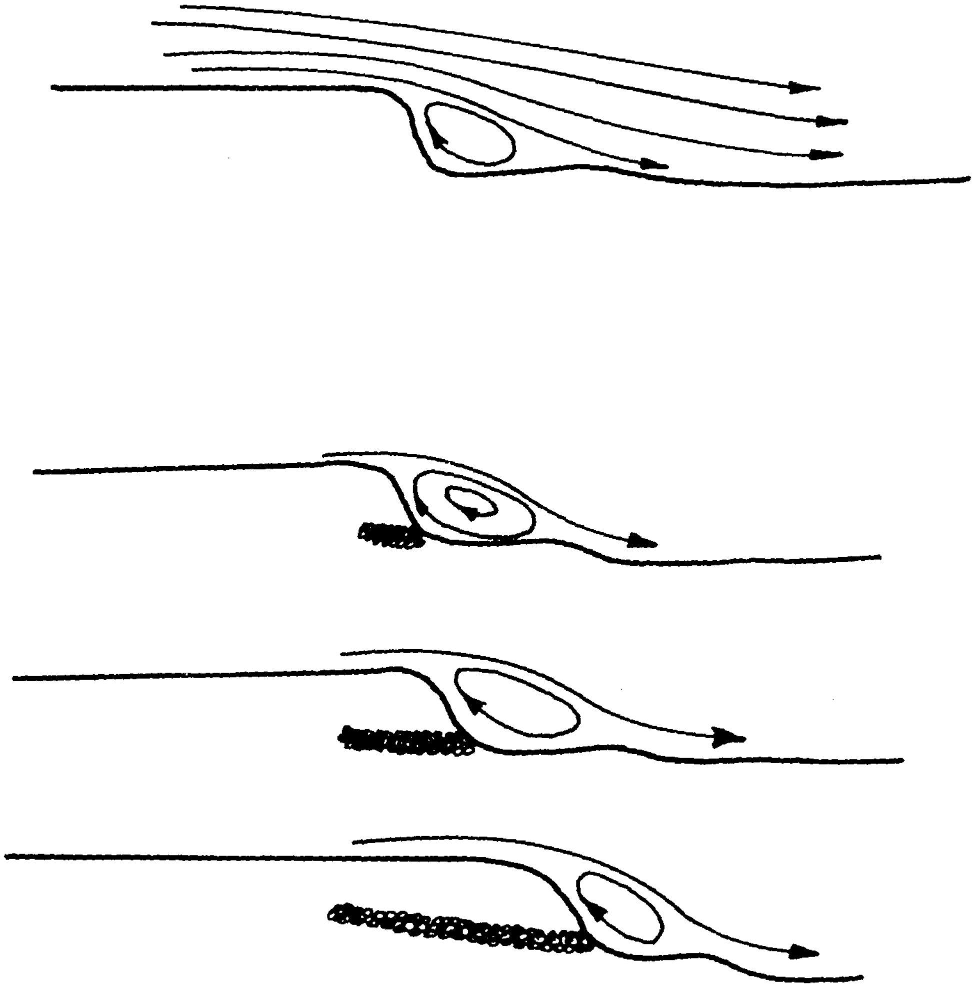


Figure 3 Dune or ripple advance by reverse rollers in zone of separation downstream of the bed forms (After Simons and Sentürk, 1976)

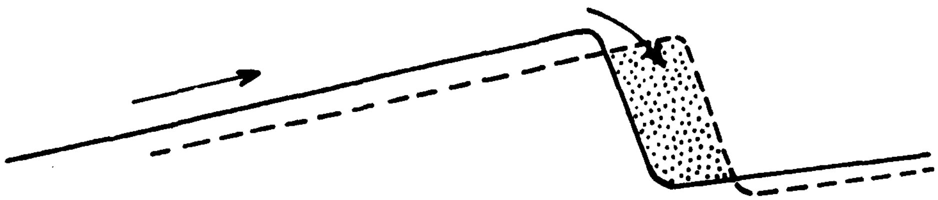


Figure 4 Dune or ripple advance by avalanching from the crest (After Simons and Sentürk, 1976)

plane bed. The water and sand waves will be in phase and they will gradually increase in amplitude until the height becomes unstable and the waves break. These waves are generally referred to as standing waves if they do not become unstable and as antidunes if they are breaking. Wave length is a function of the velocity, Kennedy (1961). When the ratio of wave height to wave length exceeds 0.14, the waves will generally break. If the antidunes do not break but remain as standing waves, the resistance to flow is not much greater than that for a plane bed condition, reduced only by acceleration and deceleration through the wave. However, if the waves break, resistance to flow increases considerably because of energy dissipation in the breaking waves. Bed material transport in antidune or standing wave conditions is extremely high and similar to that for the plane bed with some material rolling or sliding continuously along the bottom in sheets several grain diameters thick and the other material suspended in the body of the flow by turbulent eddies.

Due to unsteady flow conditions, and nonuniformity of the channel, bed forms vary considerably in space and time. Frequently, standing and breaking waves may be observed in the main thread of flow in a channel with dunes and ripples on either side. Thus, in calculating properties of bed forms, flow conditions at specific points in the channel must be used rather than average values for the whole channel. Quite frequently the bed forms do not appear to be in phase with flow conditions. This is due to the unsteady nature of the flow field and to transitions from one regime to another or one bed form to another. In some channels, the transition from dune flow through plane bed and into breaking antidune flow can be observed as a discontinuity in the flow rating curve. These transitions and calculations of bed form properties are more fully discussed in Simon and Sentürk (1976) and Simons and Richardson (1966).

2.2 SEDIMENT TRANSPORT

The bed configurations discussed in the previous section exist and change through processes of sediment transport. The sediment transport rate is a highly variable quantity, changing not only with the flow but also spatially along the channel as areas of erosion (such as on dune backs) increase the transport rate and areas of deposition (on downstream slope of dunes) decrease the transport rate. It varies temporally with the passage of flood events and the apparent migration of the bed configurations.

Not only do bed forms i.part temporal and spatial varaibility to the sediment transport rate, but they are also one of the features used by a stream to maintain some semblance of equilibrium when relatively wide deviations in the amounts of water and sediment are delivered to a reach over short time periods. When the sediment concentration supplied to a stream is relatively low, ripples and dunes which form on the stream bed offer high flow resistance, increase the flow depth while reducing the flow velocity, and thereby reduce the transport capacity of the flow. Conversely, when flow rates are high, and the potential to carry sediment is also high, the rough bed forms are obliterated leaving a bed that is relatively smooth (hydraulically) and characteristic of the transition and antidune regimes. This relatively smooth bed permits a higher flow velocity and shallower depth than would be permitted by a rougher bed and gives a higher transport capacity.

Since a lot of sediment motion may be involved in bed form changes, a hysteresis effect will be induced in the transport rate. Bed form adjustment will lag the imposed changes so that instantaneous conditions are likely different from those of equilibrium flow and transport. In view of these complexities and short term deviations, the reach can be said to approximate some average relationship between the quantities of water and sediment passing through the channel.

The goal of most transport relationships is to predict the equilibrium transport rate in terms of the conditions of the imposed flow. Few investigators have dealt with unsteady flow conditions, therefore until hysteresis lags, unsteady flows, and spatial and temporal variations are adequately investigated; expectations for a reliable, instantaneous sediment transport rate prediction are nil.

Numerous equations and procedures have been proposed in the literature for estimating the sediment transport rate. ASCE Task Committee (1971) and Shulits and Hill (1968) are two excellent review articles that treat several of the equations in detail; so only a brief discussion of them will be given here. The procedures vary in complexity from relationships between the sediment transport rate and only one flow parameter such as shear stress, mean velocity, or stream power; to basic variable correlations (Colby, 1964); and to extremely complex procedures which include state-of-the-art of transport mechanics and alluvial channel hydraulics typified, by the Einstein Bed-Load Function (Einstein, 1950).

Both review articles show great disparity between sediment rating curves calculated for the same stream reaches by the different procedures.

It should be noted that no matter how complex a calculation procedure may be, the theory becomes inadequate at some point and experimental data must be used to complete the procedure. Thus, the calculation is no better than the data upon which it is based. Furthermore, the data comes from flow-transport systems with different degrees of variability as mentioned previously. Also, the complexity of design criteria offers little advantage except for a better understanding of transport processes.

The basic variable correlation of Colby (1964) seems to do as well if not better than other methods in estimating the transport rate. This method presents the sediment transport rate as a function of depth, velocity, and particle size in a graphical correlation. A generalization of this method is obtained by normalization of the equations of motion for a sediment-water mixture (Willis and Coleman, 1969). The procedure presents the density corrected sediment concentration of the available flume data as a function of Froude number, $V/\sqrt{gy}$, in which V is the velocity, g is the acceleration of gravity and y is flow depth, and a grain diameter similitude number, $g^{1/3}d_{50}/\nu^{2/3}$, in which g is the acceleration of gravity, d_{50} is the median particle grain size, and ν is the kinematic viscosity.

Although the basic variable or similitude correlations may serve as good design tools, they give little insight into the actual mechanisms of sediment transport. The sediment transport rate is generally divided into two parts - that which moves in almost continuous contact with the bed and that which moves in suspension in the body of the flow. The suspension mechanism is the occurrence of turbulent eddies that interchange sediment between adjacent levels in the flow. A balance between the upward diffusion by turbulence and the downward settling by gravity defines the equilibrium concentration distribution for an assumed distribution of turbulent diffusivity (Vanoni, 1946). Several different models for the turbulent diffusivity have been proposed; all give comparable results in the central flow region.

Near the bed the suspension theory breaks down and some other means must be used to account for the transport in the near bed region.

Calculations made according to models based on present suspension theory give only the concentration distribution over the flow depth relative to the concentration at some arbitrary reference point. Some other independent means must be used to specify the value of this reference concentration.

The bed-load part of the sediment transport rate is often poorly defined and always difficult to measure. The bed load may be restricted to that part of the sediment load moving in continuous contact with the bed or it may be considered to be all the load moving below some arbitrary level in the flow. The near-bed transport processes are generally agreed to be strongly coupled to the shear stress on the bed or the rate that the stream expends energy per unit of bed area (stream power). The relationships for bed-load are experimental correlations that include shear stress or stream power.

The apparent downstream migration of dunes actually represents a significant transport quantity that is related to the bed-load. If the bed-load is assumed to be only that portion of the load deposited on the downstream dune faces and if dune advance by reverse rollers is neglected, dune load and bed-load become synonymous. The bed-load associated with an individual dune can be obtained from records of bed elevation and is proportional to the volume of sediment within the dune and its apparent migration speed. The average dune load is then the average of the loads associated with a number of dunes (Stein, 1965; Simons, et al., 1965). Refinements of bed-load calculations have utilized the statistical properties of bed elevation records to estimate the dune load (Lee and Jobson, 1974; Willis and Kennedy, 1977).

Potential methods for estimating the equilibrium transport rate may be summarized as either the gross variable methods or the transport mechanics methods. Gross variable methods use graphical or mathematical correlations between the independent variables (mean flow and sediment features), and the dependent variable (transport rate or mean sediment concentration). The transport mechanics approach is more complex but in general begins with a determination of the bed load from a gross variable correlation. The bed load along with assumptions for the concentration at the top of the bed layer then gives the lower concentration limit for suspension calculations. The product of local values, of concentration and velocity, from assumed

distribution models is then integrated over the flow depth to determine the suspended load. The sum of bed load and suspended load then gives the total load.

In either method, the sediment load estimates are only as good as the data, and assumptions upon which the methods are based. Because of the difficulties of obtaining reliable field data, emphasis is placed on data from laboratory flumes. Since the flows in laboratory flumes are generally small, additional data for equilibrium flows in larger flow systems are needed to test the validity of transport concepts. To supply this data, experiments reported in Appendix K of this report were conducted for flows up to 150 cfs in a large test channel.

The concepts of sediment transport discussed above assume that the hydraulics of the flow system are already defined, when in fact these may be completely unknown. About half of the complex calculations of the Einstein Bed-Load Function deal with flow hydraulics; the remainder deal with transport relationships. The following section addresses the resistance relationships that provide the dependent hydraulic variables of the transport relationships.

2.3 CHANNEL ROUGHNESS

Resistance to flow in an alluvial channel is a function of such variables as the channel geometry, channel irregularities, channel alignment and slope, characteristics of the bank and bed materials, the bed configuration of dunes and bars, rate of bed material discharge, the characteristics and concentration of wash load, temperature of the water sediment mixture, the slope of the channel and energy grade line and the intensity of turbulence. Obviously these factors are interrelated and a change in one will induce a change in others, so that it becomes very difficult to estimate values of the resistance coefficient for specific channel conditions.

Generally, all of the above variables that express some kind of channel and bed irregularity can be considered as form roughness, while the bed material size and its distribution can be considered as surface texture. When the sediment grain size, d, is large with respect to the depth of flow, D, as in mountain streams, the radio d/D is large and surface texture roughness is dominant. In alluvial channels where the grain size is very small (sand bed channels), then d/D is small and form roughness is dominant.

Both laboratory (Ackers, 1980) and field studies (Appendix E) have shown that form resistance associated with meandering is large. Ackers (1980) shows that the slope of a meandering channel (measured along the valley gradient) is at least 40% greater than that for a straight channel with the same flow rate. In many cases it is much greater. This converts to at least an 18% increase resistance in flow. Grissinger in studying the channel of Goodwin Creek in Mississippi (Appendix E) shows consistently similar results in analyzing the slope of the Goodwin Creek Channel.

The roughness of flood plains is normally very high due to the presence of vegetation and irregularities of the surface caused by both artificial and natural conditions (buildings, fences, woodlands, sand bars from previous flood events, etc.).

A measure of the relative magnitude of grain and form roughness associated with alluvial sand bed channels was presented in the discussion of bed configuration. For more information on channel resistance see Parker and Peterson (1980), Simons and Sentürk (1976), Limerinos (1970), Chow (1959), Barnes (1967), and Simons and Richardson (1962b).

Previous discussions of bed configuration, sediment transport and bed roughness indicate the complexity and dynamic nature of stream channel processes. However, if we are to be able to predict channel response and thus channel stability, it is necessary that we know how these processes affect the parameters of the models that we use to predict the response of the system. The dependence of these models on channel roughness and the significance of this dependence is discussed in the following section. Details of the models themselves are presented in Chapter 7 and Appendices I through K.

2.4 THE NATURE OF CHANNEL FLOW RESISTANCE

The mathematical modeling of flow in natural channels is usually attempted for one of two purposes. The first, the most extensively pursued, and the most understood, is modeling for the purpose of routing a flood wave down a channel. The second purpose, and the least understood, is modeling to describe local flow mechanisms associated with the processes of sediment transport and channel erosion. Models developed for the two purposes defined above are fundamentally different. The flood routing model, regardless of its mathematical nature or form, seeks to describe the passage of a flood wave down a channel from source to mouth. This model

is, in effect, regional in orientation. The local flow model, regardless of its mathematical nature or form, seeks to describe the interaction, inside a small area, between certain dynamic properties of the channel flow and certain physical, mechanical, or chemical properties of the channel bed and banks. This second model, in the most ideal sense is not regional, but is channel cross-sectional in orientation. In the less ideal and more practical sense, the local flow model is channel reach oriented, since what is usually being considered is a reach of channel in which the processes being modeled are more or less homogeneous in the direction of flow.

Although the difference between the flood routing model and the local flow model is fundamental, it is nonetheless a difference of purpose only, and not a difference existing at the beginning of mathematical treatment. This is because all flows in natural streams consist of a series of flood waves in translation down the channel. These flood waves not only move the water from one end of the channel to the other (a regional effect), they also cause temporal and spatial changes in depth of flow and mean velocity (a local effect). Thus, all rational mathematical models of alluvial channel flow have a traceable origin to the general dynamic wave equation[2]:

$$\frac{\partial y}{\partial x} + \frac{U}{g}\frac{\partial U}{\partial x} + \frac{1}{g}\frac{\partial U}{\partial t} + S_B + S_f = 0 \qquad (1)$$

where y is flow depth, x is channelwise distance, U is flow velocity, g is gravity field strength, t is time, S_B is channel bed slope, and S_f is the energy gradient due to frictional head losses. To form a particular mathematical model of channel flow, specific plausible patterns of behavior are ascribed to certain terms in equation (1) above. For example, in a flood routing model, the bed slope S_B might be supposed to vary in the channelwise direction in some manner depending on topographic or geographic factors, while S_f might be taken as a function of some supposedly constant attribute of the channel periphery, such as the Chezy roughness coefficient

2 Equation 1 is valid only for two-dimensional flows. It does not hold for streams of arbitrary cross section, and with significant lateral inflow.

C. Thus Moots (1938), in his comprehensive dynamical and geometrical treatment of the simple flood wave, expressed S_f as:

$$S_f = \frac{U^2}{C^2 y} \tag{2}$$

With this relation inserted, equation (1) became a sufficient mathematical model for a flood wave in a wide rectangular channel, and it was only necessary for Moots to assume constant values of S_B and C to successfully simulate the sequence of maximum velocity, discharge, and stage in a rigid channel. In short, a flood wave could be routed down the channel. More recent flood routing models, while taking into account such added variables as influx of water from tributaries, and regional changes in channel size, shape, and slope, nonetheless essentially follow the same basic principle. In contrast, in a local flow model, S_B and S_f must follow patterns of rapid change with time. The situation with regard to the bed slope S_B is not critical when a channel reach is considered, because S_B can vary only within certain topographic constraints. Whereas common observation indicates that channel bed configuration responses to changes in streamflow, lag considerably behind the streamflow changes. The friction slope S_f however, is immediately responsive to flow changes, and is also affected by the lag in channel bed response. Thus, the principle problem in formulating a local flow mathematical model is evidently one of specifying a plausible pattern of time variation for S_f throughout the runoff event being simulated. This is why it is important to understand alluvial channel flow resistance.

2.5 TIME VARIATION OF RESISTANCE COEFFICIENTS IN EPHEMERAL RUNOFF EVENTS

Early efforts at understanding streamflow incorporated an assumption that a channel had a fixed roughness that could be represented by a numerical value, and that this numerical value could be taken as constant for channel boundary material having defineable characteristics; for example, channel boundaries composed of wood, or of mud, sand, gravel, cobbles, etc. However, Keulegan (1938), demonstrated the utility of the Nikuradse (1933) pipe flow resistance concepts in understanding steady open channel flow with rigid boundaries; thus opening the way to general studies of flow in channels with all sorts of boundaries, including those composed

of alluvium. This work also introduced the more sensitive and versatile Darcy-Weisbach flow resistance coefficient in place of the older, supposedly constant roughness coefficients. The Darcy-Weisbach coefficient can be written:

$$f = \frac{8\ U^{*2}}{U^2} \tag{3}$$

where U^* is the shear velocity at the channel periphery. Brooks (1958) deeply perturbed hydraulicians by showing, in careful laboratory experiments, that in flows over sand beds, neither f nor the older Chezy coefficient C could be considered constant for a given channel, and that furthermore, they did not vary with flow according to single-valued functions, but according to multi-valued functions related in some complicated way to the sequential appearance of ripples, dunes, and antidunes on the channel beds. Some four years later Coleman (1962) published the first systematic study of the time variation of the Darcy-Weisback coefficient in the unsteady flows of ephemeral runoff events. This study showed that f was subject to considerable variation in magnitude during a runoff event. It was also found that, in the five events observed, low f values were associated with the higher discharges, and that, for a particular event, the minimum f value occurred a few minutes before actual peak discharge. For the five events observed, no general form was found for the shape of the curve of f against time. Each event seemed to have a unique curve, the form of which evidently depended on the duration and magnitude of the runoff event, and not directly on processes occurring in the channel. No model for the variation of f throughout a runoff event could be formulated, and therefore this study contributed little to the possibility of constructing local flow models based on equation (1). Thus, a gap still exists in the knowledge needed to use equation (1) completely, and until alluvial channel resistance in ephemeral flows is more fully understood, this gap cannot be eliminated.

Appendix N on alluvial channel flow resistance describes a laboratory experiment that elaborates more on the problem of time variation in the roughness coefficient.

2.6 TURBULENT FLOW PROPERTIES RELATED TO FLOW RESISTANCE AND SEDIMENT TRANSPORT

Previous discussions of sediment transport and channel roughness concentrated on problems encountered in incorporating these concepts in flow and sediment routing models. Another aspect of resistance to flow that was mentioned previously and is directly related to sediment transport is flow turbulence. Other than recognizing its existence, and its influence in suspension and mixing, it has not been incorporated in any transport equations. Significant improvement in these equations probably depends upon documentation of these forces and their incorporation in the routing formulations. Equation (3) can be rewritten as :

$$\frac{\tau_o}{\rho} = U \sqrt{\frac{f}{8}} \tag{4}$$

where ρ is the bulk density fo the flow, and τ_o can be interpreted as an averaged value of the shear stresses exerted by the cross-sectional channel perimeter on the flowing water. These stresses are balanced by equal forces generated by the water on unit wetted areas, and known as tractive forces. Knowledge of the forces acting on channel banks and beds are essential for proper design of stream bank protection. Over the years several models have been postulated for estimating the cross-sectional variation of tractive forces in prismatic channels. In general, these models are in poor agreement with field observations. The lack of agreement stems in part from postulating the existence of a velocity distribution without secondary flow. However, secondary currents in straight channels can have an important effect on tractive-force redistribution indirectly, because of the distortion which they cause to primary isovels (Thorne et al., 1980). The above disagreement also arises from ignoring the turbulent nature of the streamflow. The existing tractive-force models are based on the estimation of time-averaged shear stresses, somehow related to gross-flow parameters, and disregard the actual distribution of the instantaneous values of point tractive forces. In turbulent flows such forces are not constant but are dependent on the local turbulent velocity field, and vary with time at frequencies of the same order as the turbulent velocities. It has been observed that scouring

of bed material can take place at values of time-averaged shear stress well below the value of critical stress defined by Shield's function. This has been interpreted to indicate that different scouring rates can be expected for shear stress distributions with different variances but equal mean values. This illustrates the limitation of stability analyses which characterize channel-boundary forces with the ensemble average of their statistical distributons. It also emphasizes the need to collect data on the spatial and probabilistic distribution of hydrodynamic forces acting on the boundaries of open channels. This need led to the experimental study reported in the Appendix L. This appendix reports measurements of some stochastic properties of instantaneous tractive forces taken along the wetted perimeter of a prismatic open channel. The results of the study have been presented by Wylie et al. (1977).

2.7 STREAMBANK AND STREAMBED MATERIALS

The material that makes up the bed of a stream channel influences to a large degree the sediment transport, the forms of bed roughness, resistance to flow and ultimately the channel geometry as discussed in the next section. Bed material ranges from entrained clay and silt through sand and gravel to rock sizes. Particle sizes associated with this gradation are shown in Table 1 for the USDA textural classification. There are slight variations in this breakdown depending upon the classification system used. However, the differences are minor and mostly relate to the dividing line between silt and sand.

Table 1. USDA particle size classification according to particle diameter

clay	< 0.002 mm
silt	0.002 mm - 0.05 mm
sand	0.05 mm - 2.0 mm
gravel	> 2.0 mm

Several variables are used to describe the bed material. These are size, the size distribution, the particle shape, and the mass density. The most common measure of larger sediment particle sizes is sieve diameter. However fall diameter is an alternate measure used for smaller particle

sizes. The advantage of using fall diameter as measure of effective size is that it combines the effects of the particle size, shape, and roughness; all of which are important in estimating sediment transport. Several standard procedures use fall velocity to characterize sediment particles. The pipette bottom-withdrawal tube, and hydrometer are the most commonly used methods of determining the size distribution of fine sediments, those less than 0.05 mm. Two generally accepted methods for determining the particle size distribution of sand-size particles are sieving and visual-accumulation (VA) tube methods. The size distribution based on sieving quantifies the distribution by physical diameter, whereas the VA tube methods quantify it by fall velocity. Gravel and rock size particles can be established by sieving the smaller sizes and using photographic, grid, and direct measurement techniques on the larger particles. Standard laboratory procedures have been established for all of these techniques. They are described in Chapter 3 of the National Handbook of Recommended Methods for Water-Data Acquisition published by the U.S. Geological Survey.

From the size distribution of the material, various parameters may be defined that are helpful in analyses. The cumulative size distribution from fine to coarse will indicate the percent of material finer than any particular size. For example, the d_{95} is the size of material for which 95 percent of the material is finer. If points from the cumulative size distribution are plotted on log-probability paper, and they fall on a straight line, the distribution is assumed to be log-normally distributed. However if the data vary widely from a straight line, they would not be considered log-normally distributed. If the data plot as two or more steep line segments separated by very flat segments, then the distribution is likely bimodal or possibly multi-modal. If the data plot as a single, nearly straight line, the slope of the line is inversely proportional to the gradation of the material. The gradation or standard deviation is a measure of the size distribution of the material. It measures the average difference in particle size within which about 2/3 of the sample will lie. The standard deviation is approximated by the gradation coefficient which is defined as

$$\alpha = 1/2 \left[\frac{d_{84}}{d_{50}} + \frac{d_{50}}{d_{16}}\right] \tag{5}$$

If the particle size distribution is log-normal, i.e., plots as a straight line on log-probability paper, then

$$d_{84}/d_{50} = d_{50}/d_{16} = \sigma. \tag{6}$$

It is possible to analyze the cumulative distribution with readily available computer programs to determine other parameters of the distribution, i.e., the mean, variance, skewness and kurtosis.

Particle shape is normally defined by the shape factor, S_p, (Corey, 1949) defined as

$$S_p = c/\sqrt{ab} \tag{7}$$

in which a, b and c are dimensions of the three mutually perpendicular diameters of the particle; c is the minor axis.

The angle of repose is of particular interest in stability analyses. It increases both with particle size and angularity and is less in water than dry. See Simons and Sentürk (1976) pages 196-198 for further information on its evaluation and significance.

In general there is a tendency for stream channels that have developed in fine grained materials to have a smaller width-depth ratio than channels located in coarse grained materials. This is in part due to the differing quantities of material being transported, the channel slopes, and the effect that the material size has on the bank slopes. The characteristic differences in shape of channels in fine sediments as opposed to channels in coarse sediments is discussed in the section on geomorphic relations; where it is shown that the width-depth ratio is inversely proportional to the percent of fines in the bank (Schumm, 1977 and Lacey, 1930). Parker (1979) discusses in considerable detail the geometry of gravel rivers and presents power-law type relations for the hydraulic geometry of gravel channels.

Since the particle sizes being transported in a stream channel are directly proportional to some dominant velocity of the water, there is a general tendency for the bed materials to get finer in the downstream direction. This is due to the tendency of a stream system toward flatter slopes in the lower reaches. What happens to any given channel, however,

depends upon many things, especially the particle size distribution of sediments from major tributaries and natural grade controls, the geology that influences bed slope, and volume of runoff.

The gradation and distribution of bank materials is more variable than that of the channel bed. The banks may consist of fine or coarse material, cohesive or noncohesive material, homogeneous or nonhomogeneous material, stratified material, or some heterogeneous combination of these materials. The near surface geology of the area is probably the most significant factor in determining the characteristics of the bank materials. In hard rock country, the head waters will consist of narrow v-shaped channels with little or no defined bank line. In this case the bank material is likely to be coarse angular rock. Downstream in the wider valleys, the bank material will be a combination of rock, gravel and sand with small quantities of silt and clay. Further downstream in the wide flood plain areas the bank material will become finer with larger quantities of silt and clay, extensive quantities of sand and more limited quantities of gravel. In these lower reaches the banks may be more stratified due to the deposition pattern of material laid down in the geologic past.

In areas of the country where tributary headwaters do not lie in hard rock geologic deposits, the bank and bed materials are likely to be much finer and may consist entirely of sand, silt and clay.

In the alluvial areas of large river systems such as the Mississippi River, the nature of the bank and bed materials are influenced considerably by the ancient gravel deposits or isolated pockets of re-worked river gravels and sands.

In almost all cases the banks of channels in valleys with a developed flood plain vary considerably from place to place. This is due to the deposition pattern of ancient sediments and the re-working of bank and bed materials as the channel migrates back and forth through the valley. Old abandoned channels may be filled with silts and clays, and relict-natural levees along the channels, buried. The random nature of the materials in the banks of these channels leads to widely varying degrees of stability. Sand lenses underlying cohesive materials may lead to severe bank caving problems as the sand is winnowed out. Seepage along planes of highly impermeable material can cause slips or mud flows. The intersection of abandoned channels may expose either highly erosive or stable material

depending upon the relative cohesiveness of the material deposited in the abandoned channel. In larger channels, areas of instability can be rendered stable by the natural deposition of fine material that is deposited along the banks under water during flood periods. These berms of fine material are usually less erosive than the bank materials, and if vegetation becomes established can provide protection for prolonged periods.

Generally river systems are classified as those lying in hard rock country or not in hard rock country. In hard rock country, the elevation and grade of the channels are controlled by the bed rock. In areas not associated with hard rock, the channels are usually assumed to be alluvial with the channel grade being controlled by the size of the material in the channel and the water and sediment load imposed upon it. However there is another level of control that is frequently overlooked in alluvial channels. That is a temporal control exerted on the base level of the stream by highly resistant strata such as iron-stone and similar deposits. These controls which can last for many years are dominant and can significantly control channel behavior in an otherwise completely alluvial channel. For a more complete discussion of the impact of bed controls such as this, see Chapter 5 and the discussions in Appendices A, B and E.

2.8 RIVER PATTERN

The term channel pattern refers to the configuration of a limited reach of a river that can be defined as straight, sinuous, meandering, or braided. Figure 5 shows examples of some common channel patterns. Channel patterns do not fall easily into well-defined categories because there is a gradual merging of one pattern into another. The difference between a sinuous course and a meandering one is a matter of degree of sinuosity and of the symmetry of the successive bends. Simularly, there is a gradation between the occurrence of scattered islands and a truly braided pattern.

Truly straight channels are rare to the point of being nonexistent. It is possible to find short reaches that may be straight but very rarely do the straight segments exceed a length ten times the channel width (Leopold and Wolman, 1957). Within straight reaches the thalweg or line of

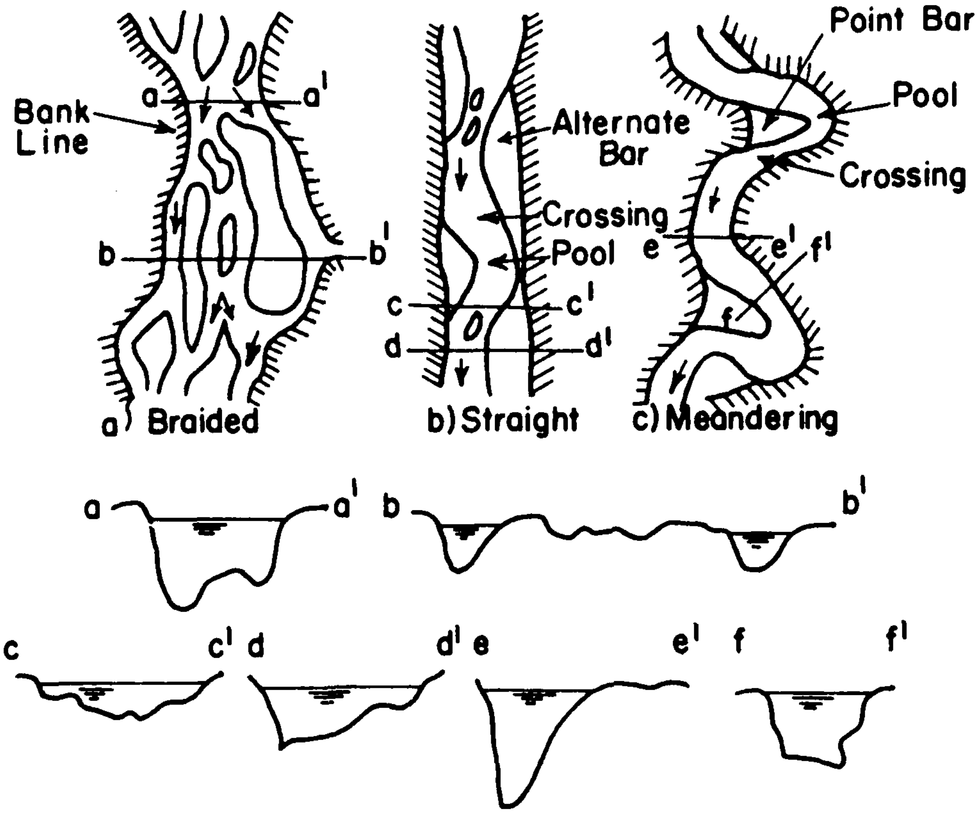


Figure 5 Channel patterns (After Simons and Sentürk, 1976)

maximum depth wanders back and forth from one bank to the other. Mud deposits or sand bars are commonly found opposite the deepest point. Between these bars, where the thalweg crosses to the opposite bank, the channel is normally quite shallow compared to the pools inbetween.

Frequently the straight reaches are only transitions in the continually changing plan of a river system. At points where the thalweg is close to the bank, erosion is likely to occur. This can lead to development of a sinuous pattern. In sinuous channels deep pools are carved adjacent to the concave (outer) bank by relatively high velocities. The centrifugal force in the bend causes the water surface to be higher at the outside bank. This transverse slope causes a helicoidal flow in the bend that sweeps the bed material load toward the convex (inner) bank where it is deposited forming the point bars previously discussed. Scour in the bend causes the bends or meanders to migrate downstream and sometimes laterally. Some of the sediment eroded from the outer bank is deposited in the point bar downstream gradually building up the inner bank as the meander migrates down the valley. Generally, the velocities and sediment loads of sinuous channels are moderate. Crossings between the pools in the bendways are comparatively shallow and are commonly called riffles.

As the sinuosity of a channel increases, the width of the channel tends to increase in the bends and the point bars become larger. Bank vegetation also plays a large role in the rate of bend migration. On the banks, grass and small shrubs protect the surface from high velocities and trap fine materials, thus increasing resistance to failure and erosion. Roots from large trees also tend to stabilize the banks in bendways and can significantly slow the erosion of these areas.

A braided stream channel is one in which there are two or more main channels that intersect, giving a braided appearance. Between the sub-channels there are numerous sand bars and islands that change frequently and rapidly. Even though they give the appearance of an aggrading channel, they may be in equilibrium with the imposed sediment and water load. Generally, the channels are wide and shallow, they have steep slopes, high velocities and carry large concentrations of coarse sediment. Some time small changes in the conditions of a channel or the load imposed upon it can cause a sinuous channel with isolated bars to become a braided channel and vice versa.

River patterns, straight, meandering or braided, are related to the sediment load, channel slope, and discharge rate. Schumm (1977), shows relations between slope and discharge (See Figure 6) attributing them to Leopold and Wolman (1957), Lane (1957), and Ackers (1964). Some of the differences between the relations are due to differences in reference discharge and slope. There is an obvious threshold between meandering and braided channels and also indications of a threshold between straight and meandering at very low slopes. Laboratory experiments tend to support this. Plots of sinuosity vs channel slope or stream power also show similar relations (Schumm, 1977), pgs. 121-131. The significance of these thresholds is indicated by the following quote from Schumm (1977):

> "It appears that for a given bed and bank material and discharge there is a lower threshold of stream power below which the flow is not capable of eroding the banks, and cross-channel currents are incapable of moving bed sediment to form alternate bars. There is an upper threshold of stream power, above which velocity and Froude numbers are high. Bank erosion is vigorous, and a wide braided channel forms with little influence of cross-channel currents. In the zone between the upper and lower thresholds meandering occurs. The banks erode but they have sufficient resistance to preserve the sinuous pattern and cross-channel currents form alternate bars which develop into point bars.
>
> Therefore, depending on the initial channel's stream power, a slight increase or decrease of stream power (velocity) can significantly alter sinuosity if the river plots near a pattern threshold. This means that pattern can be altered, perhaps significantly, by a change of discharge, channel roughness, or any other factor that influences velocity."

For additional information on river pattern see Kellerhals (1980), Schumm (1977), Leopold and Wolman (1975), Culbertson et al. (1967), and Leopold et al. (1964).

2.9 FLOW IN BENDS

Water flowing through a bend will have a free surface on the outside of the bend that is higher than the inside elevation, See Figure 7. This is caused by centrifugal forces acting on the water. The superelevation or

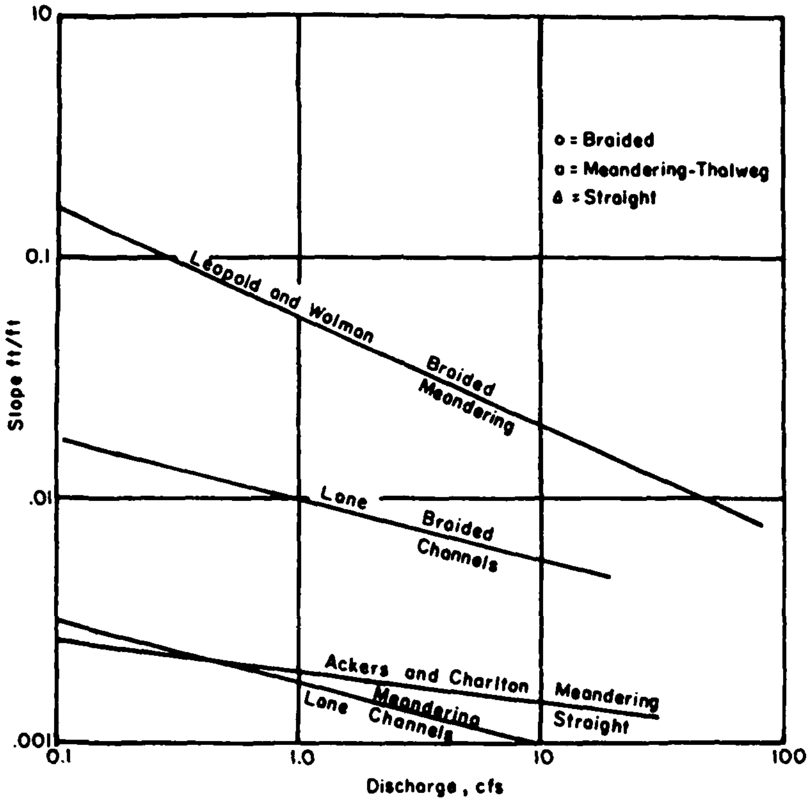


Figure 6 Relation between slope and discharge, at thresholds between river patterns (After Schumm, 1977)

Figure 7 Super elevation of flow in a bend of Pigeon Roost Creek in Mississippi

transverse slope of the water can be calculated from the dimensions of the bend. However, solution depends upon the assumed velocity distribution across the channel. Little information is available in the literature upon which to make this judgment. Simons (1979) reviews solutions for several assumed velocity distributions.

The cross channel slope of water in the bend causes a transverse component of flow near the bed from the outer bank to the inner bank. The transverse flow erodes the bed of the channel near the outer bank and sweeps the material across the channel developing the point bar observed on the downstream inner bank. The depth and location of maximum scour are functions of the intensity of the cross channel velocity component which is dependent upon the longitudinal velocity, the angle of the bend, the cross sectional shape of the approach channel (width-depth ratio) and the channel width. See Simons (1979), Bathurst et al. (1979) and Einstein (1971).

Bendways in many natural streams have a relatively narrow range of values of the ratio of the radius or curvature, R, (of the mid-stream line) to the top bank width, w, Leopold and Wolman (1960). Bagnold (1960) attributes this to flow separation near the inner bank; at a value of R/w near 2 separation reaches a maximum intensity. Hickin and Nanson (1975) in studies of the Beaton River in British Columbia, show that maximum bank erosion and channel bend migration are correlated, with a very narrow range of R/w values. Maximum bank erosion was observed at a [illegible] R/w = 2.1, and maximum channel bend migration at 2.4 < R/w < 3.[illegible]ates of bank erosion are considerably less for larger and smaller R/w values. This may be explained by the fact that as R/w declines to values less than 3.0, the maximum velocity filament shifts from the concave (outer) bank to the convex (inner) bank. This results in high shear stress over the point bar preventing further deposition, and reduced shear stresses along the outer bank thus reducing the rate of erosion and channel migration, Hickin (1978). These observations could be quite helpful in assessing the likelihood of bendway erosion for given values of R/w.

Transverse velocity components are also observed in straight or nearly straight channels. However, the exact pattern or cause of these currents is not well know. Reduced velocities along the banks can induce a circulation pattern that tends to propagate itself across wide shallow

channels in the form of opposing horizontal rollers. These lead to areas of upwelling and downwelling and in some cases sediment deposition patterns that indicate their existence. The location of trash on the surface has also been observed as an indication of such currents. See Hickin (1978) for a discussion of secondary currents as observed in the Squamish River in British Columbia.

2.10 GEOMORPHIC RELATIONS

In the above paragraphs, variations in the plan form of stream channels was discussed. In this section, geomorphic relations of channel size, shape, and sinuosity are described.

The dominant factor in determining channel size is quantity of water that the channel carries. For most rivers, the water surface width, b, depth, d, and velocity, v, and be expressed as:

$$b = k_b \, Q_m^{c_b} \tag{8}$$

$$d = k_d \, Q_m^{c_d} \tag{9}$$

$$v = k_v \, Q_m^{c_v} \tag{10}$$

in which Q_m is the mean annual discharge and k and c are coefficients. Leopold and Maddock (1953) propose that c_b and c_d are 0.5 and 0.4 respectively but that k_b and k_d are different for each river. Leopold et al. (1964) discuss these relations 'at a station' and show that since b x d = A, the cross sectional area of flow, then for a given depth, v x a = Q, the flow for that depth, thus $c_b + c_d + d_v = 1.0$ and $k_b \cdot k_d \cdot k_v = 1.0$. A comparison of 'at a station' exponent values with average downstream relations is presented in Table 2. Relations for sediment transport rate, water surface slopes, and Manning's n are also shown.

Channels in areas of the country that experience short high intensity storms tend to have high ratios of Qp/Qm where Q_p is the mean annual peak flow and Q_m is the mean annual flow. In general, channels in these areas are generally straighter and have a large width to depth ratio, whereas

Table 2. Values of exponents in the equations for the hydraulic geometry of river channels. (After Leopold et al., 1964)

	Average At-a-station Relations						Average Downstream Relations (bankfull or mean annual flow)					
	b	f	m	j	z	y	b	f	m	j	z	y
Average values, midwestern United States[1]	.26	.40	.34	2.5			.5	.4	.1	.8	-.49[4]	
Brandywine Creek, Pennsylvania[2]	.04	.41	.55	2.2	.05	-.20	.42	.45	.05		-1.07	-.28
Ephemeral streams in semiarid United States	.29	.36	.34				.5	.3	.2	1.3	-.95	-.3
Appalacian streams[3]							.55	.36	.09			
Average of 158 gaging stations in United States	.12	.45	.43									
10 gaging stations on Rhine River	.13	.41	.43									

Equation Forms: $w = aQ^b$, $d = cQ^f$, $v = kQ^m$, $G_s s = pQ^j$, $S = tQ^z$, $n' = rQ^y$.

Symbols:

- Q, discharge.
- w, channel width.
- d, mean depth.
- v, mean velocity.
- Gs, suspended load transport rate.
- s, water-surface slope.
- n', roughness parameter of Manning type.

1/ Leopold and Maddock (1953, p.26).

2/ Wolman (1955, pp. 23, 26).

3/ Brush (1961, p. 160).

4/ Leopold (1953, p. 619); using other data, Langbein obtained value of X = -.75.

channels that have a low Qp/Qm ratio have a more sinuous channel with low width to depth ratios (Stevens et al., 1975, and Gupta, 1975).

As mentioned previously, the sediment load significantly influences the shape of a river channel. Lacy (1930), in his analysis of regime flows in canals shows that coarse sediment produce channels with a high width-depth ration and that fine sediments produce narrow, deep cross sections. The channel shape is also closely related to the percentage of silt and clay, M, in the sediments forming the perimeter of the channel, Schumm (1977). The expression obtained from stable channels is

$$F = 255\ M^{-1.08} \tag{11}$$

in which F is the width-depth ratio. Schumm (1977, pages 109-110) discusses the relation between bed load size and bank materials for five locations where total sediment load data and percentage of fines in the banks were known and found

$$M = \frac{55}{Q_b} \tag{12}$$

in which Q_b is the percentage of total load that is bed load. Schumm (1977) also combines both M and Q_m, the mean annual discharge, in expressions for width and depth to get

$$b = 37\ \frac{Q_m^{0.38}}{M^{0.39}} \tag{13}$$

$$d = 0.6\ M^{0.342}\ Q_m^{0.29} \tag{14}$$

The gradient, or slope, of a stream usually decreases in the downstream direction as the volume of flow increases and the sediment sizes decrease. This was shown qualitatively by Lane (1955) as

$$Q_s d_{50} \sim Qs \tag{15}$$

in which Q_s is the sediment discharge, Q is the water discharge, s is the gradient and d_{50} is median sediment size. Coefficients to quantify the relation are a function of the type of rock in the region, the distribution of sediment sizes in transport and local controls such as bed rock or clay

sills. See Schumm (1977) and Leopold et al. (1964), for additional information.

The sinuosity, P, of a stream is the ratio of the channel length to valley length. One would normally assume that a stream channel slope would be directly related to the valley slope. However, this is not necessarily the case. The slope of the valley was determined by hydrologic conditions during past geologic periods. Thus, valley slopes are a function of base level changes that may have occurred, changes in climate, and changes in the size of transported sediment. If a valley slope is such that a stream system can move its water and sediment through the valley, then it will flow straight. In most river valleys this is not the case because of changes such as mentioned above. Most situations are such that the sediments in the valley are finer, and thus the equilibrium slope of the channel must be less than that of the valley gradient. The only way that a channel system can come to equilibrium in such a situation is to incise or to meander across the valley, thus reducing its gradient. Incision is not likely to occur, even though it does in some cases, because the general tendency is for sediments to increase in size with depth in the alluvium. Frequently, armoring of the bed will prevent further degradation, thus the channel will develop a sinuous path with a lower gradient to dissipate the energy in excess of that needed to transport the sediment and move the water. A second reason why the channel is more likely to develop a sinuous path is that channel incision increases the proportion of flow in the channel as compared to the out-of-bank flow. Lane's equation shows that an increased flow requires a lower slope if the amount and size of sediment transported remain the same. Thus, incision only aggravates the problem and channel meandering is more likely to occur. In a given river system the meandering will develop until there is an optimum balance between channel slope, depth, overbank flooding, and the sediment in transport. In river systems where the valley gradient changes, in response to tectonic activity or ancient depositional patterns, there is frequently a corresponding change in sinuosity. This is an effort on the part of the stream to maintain a fairly uniform channel slope. Thus in the steeper reaches, sinuosity will be greater than in the flatter reaches. See Schumm's (1972) discussion of The Mississippi and Jordan Rivers.

Since the channel is continually changing location in uncontrolled reaches, there is a tendency for it to show changes in sinuosity over time.

Variations in bank materials and the hydraulic conditions in bends cause nonuniform erosion rates, thus the meanders will vary in amplitude. These variations and the migration cause cutoffs to occur. When this happens, the slope of the channel increases, precipitating an increase in erosion rates. Downstream deposition will decrease the slope causing more over bank flooding. These processes cause further cutoffs to develop resulting in a drastic reduction in local sinuosity. However, after a period of time, new meanders will develop, and grow, and the pattern will repeat itself. These variations in sinuosity fluctuate about an average value that is probably optimum for the water and sediment load of the stream. Winkley (1980) discusses this, as it relates to selection of an optimum alignment for the Lower Mississippi River.

For alluvial channels, the percentage of fine materials in the banks of a stream channel is indicative of the material in transport. Figure 8 shows how this percentage influences the channel gradient for a given valley slope. In the Great Plains, the relation between sinuosity, P, and percent silt-clay, M, is

$$P = 0.94\ M^{0.25} \tag{16}$$

(Schumm, 1977).

The meander wave length, λ, the distance from one meander to the same point on the next meander on the same side of the valley downstream, is also frequently related to these same charateristics. See Schumm (1977, pages 113-117). The general form of the relationship is

$$\lambda = a\ Q^{b}\ M^{c} \tag{17}$$

in which a, b and c are coefficients, Q is some representative flow and M is the percent silt-clay in the sediment load. The most significant relation is

$$\lambda = 1890\ Q_{m}^{0.34}\ M^{-0.74} \tag{18}$$

in which λ is in feet (Schumm, 1977). The average error of this relation is 16 percent. If bankfull stage is considered as the only predictor, the relation is shown in Figure 9. At a given flow rate, meander wave length

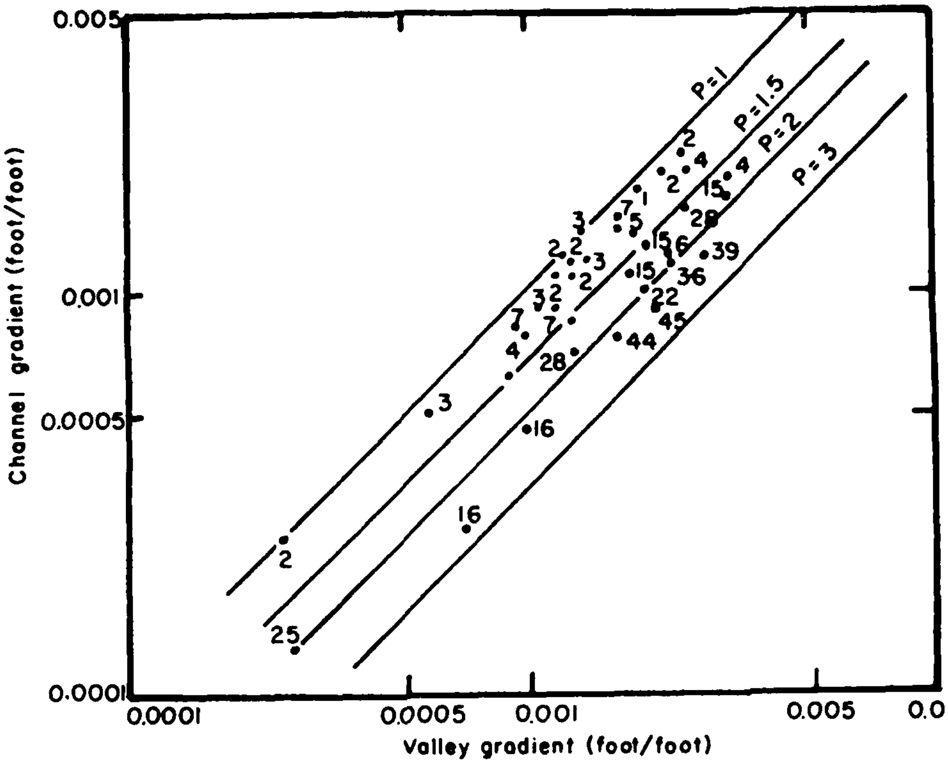


Figure 8 Relations between alluvial valley slope and channel gradient. Numbers beside points indicate precentage of silt-clay in the channels. Four lines of equal sinuosity (P) are shown. (After Schumm, 1977)

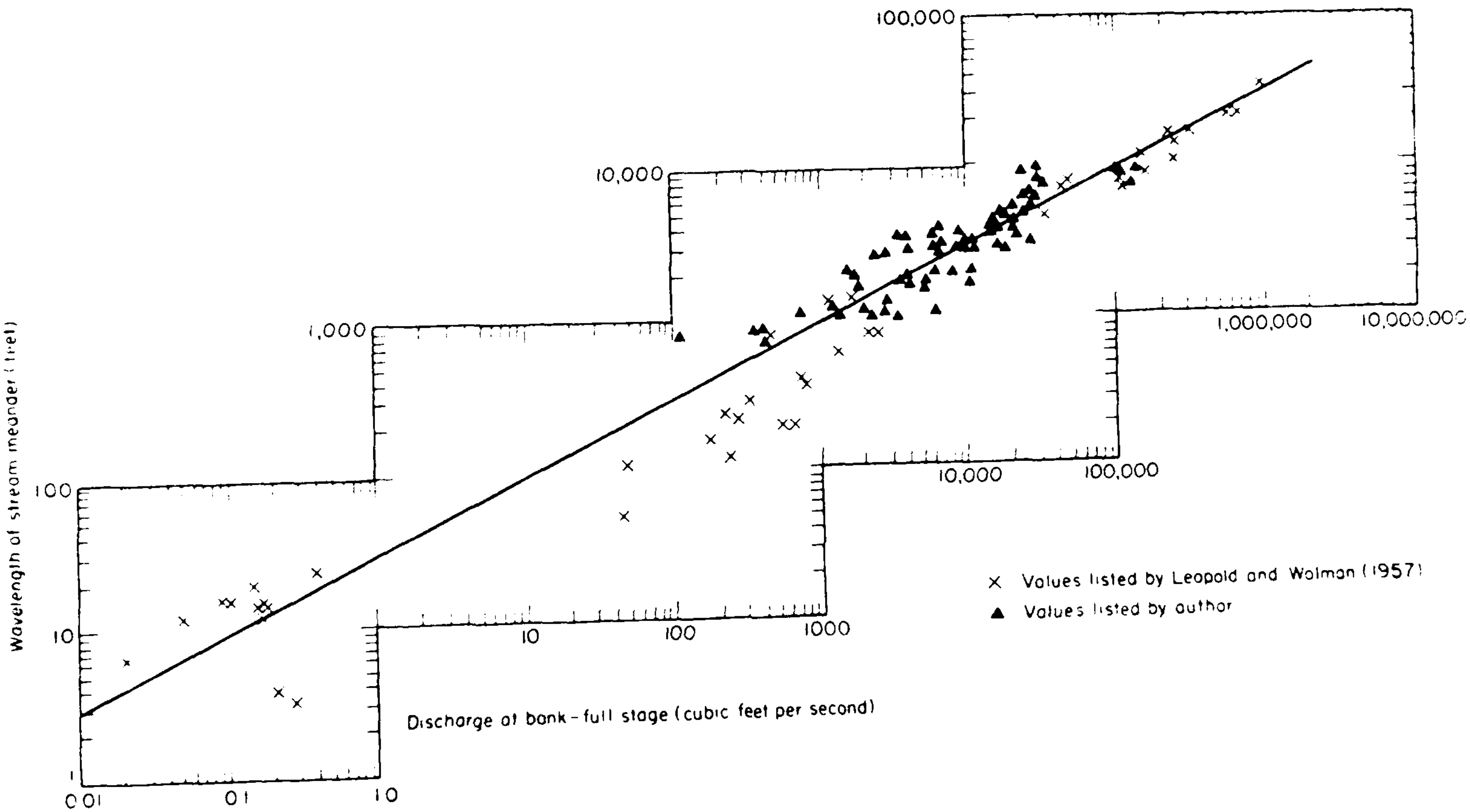


Figure 9 Relations between meander wavelength and bankfull discharge (After Schumm, 1977)

can have nearly an order of magnitude variation, but a consistency over nearly 8 orders of magnitude in flow rate is shown.

To demonstrate the effect of changes in flow or sediment load on channel morphology, the previous discussion can be summarized as follows (Symbols are as previously defined):

$$Q \sim \frac{b,\ d,\ \lambda}{s} \tag{19}$$

and

$$Q_s \sim \frac{b,\ \lambda,\ s}{d, P} \tag{20}$$

These expressions may be used separately or in combination to analyze expected changes in channel configuration due to induced changes in water or sediment load. For additional discussion of use of these and similar expressions, see pages 133-137 of Schumm (1977), pages 5-61 to 5-75 in Simons (1979), and pages 45-62 in Simons and Sentürk (1976).

3 WATERSHED PROCESSES AND THEIR IMPACT ON THE CHANNEL SYSTEM

The size, shape, slope, stability and other features of a stream channel system vary both spatially and temporally and are a direct response to the flow of water and sediment imposed upon it. Spatial variability comes from the numerous land uses and soils lying in the watershed. Both land use and soils affect the volumes and rates of runoff. The amount of surface runoff depends on the absorption characteristics (infiltration and interception) of upland areas and the rate of runoff depends on the hydraulic characteristics of the upland flow system that affect conveyance and detention.

The sediment load of the runoff depends on (1) the erosion rate and (2) the physical characteristics of the eroded sediment that affect the potential for subsequent deposition of this sediment before it reaches the channel. Most watersheds include numerous different land-use conditions that vary in rates of sediment production and runoff. Knowledge of such rates for various typical watershed conditions provides a basis for determining their impact on channel stability.

The amount of water discharged to the channel system depends on the infiltration capacity of each subcatchment. Infiltration capacity is related to a multitude of factors, especially antecedent soil moisture and surface seal development. By determining changes in the soil water state in selected subcatchments, the gross response of the watershed to incident rainstorm events can be evaluated.

Temporal variability of the stream channel system comes in response to the dynamic nature of the inputs of water and sediment. If there are no major changes in these loads over long periods of time, quasi-steady states of equilibrium are established and they are reflected in the channel characteristics. However, if major changes in either or both, the input of water and sediment occur, then we can expect to see corresponding changes in the channel characteristics.

It is, therefore, important to consider the source of inputs to the channel system. Various interrelated factors work to dictate the source and impact of sediment on the channel system. These factors include the type of sediment, precipitation, runoff characteristics of the streams and rivers, vegetation and man's alteration of the natural system. As these and other factors vary both spatially and temporally so do the sources and

impacts of sediment. Sediment sources can be divided into two broad groups; upland watershed sources and channel sources.

3.1 UPLAND WATERSHED SEDIMENT SOURCES

The quantity and characteristics of sediment from upstream sources are influenced directly by man's activity and the characteristics of storms, but first we need to examine the watershed from which the sediments come.

There are many ways to categorize upland watershed sediments, but perhaps the most logical is by their sources. Typical sources are land surface erosion, gully formation, and mass wasting processes. Except in dry rangelands of the West, vegetative protection of the soil surface reduces the contribution from well managed pasture, range, or forested areas to negligible amounts. An exception; which is the influence of gullies, roads and channels that lie in these areas; is discussed below. Thus, the major land surface sources are open lands associated with farming operations, gullies or construction sites.

Sediment is removed from both farmed land and construction sites by rill and interrill erosion. Interrill erosion is a relatively uniform removal of material by raindrop impact and surface runoff from the soil surface between rills. Runoff usually flows only a short distance before it concentrates into small channels or rills. Flow concentration results from previous erosion, vegetation patterns, microrelief and alteration of drainage patterns by man as from tillage operations. Erosion of material in the rills is caused primarily by the force of the flowing water. It is advantageous to separate erosion into rill and interrill components because the rates of erosion between the two can vary considerably depending upon topography and cover. Interrill erosion is primarily a function of rainfall intensity rather than slope (Harmon and Meyer, 1978). In contrast, rill erosion is primarily a function of slope (Meyer et al., 1975). Thus, accurate estimates of erosion rates from open land need to be made from the separate sources (Foster and Meyer, 1975). This is particularly important in longer slopes because of the relative importance of rill flow compared to interrill flow, Meyer (1974) discusses these processes as they apply to urban or construction site erosion. In grassland and forested land, overland flow has the same rill and interrill characteristics, but vegetation protects the interrill areas from raindrop

impact and reduces the velocities of the concentrated flows to a point where very little erosion is observed. Erosion rates from cropland range from low rates of less than 1 ton/acre/yr to over 100 tons/acre/yr.

Gullies are another source of sediment. However, unlike surface erosion, the causes of gully development are less easily defined because of their complexity. The predominant processes recognized in gully development include mass wasting of gully scarps and transport of the resulting material (Bradford et al., 1973; Bradford and Piest, 1977; and Piest et al., 1975). Many of the same mechanisms discussed in the section of this report dealing with channel erosion are equally applicable to gullies. Erosion rates from gullies are much greater than those from farm fields and range up to 300 tons/acre/yr; however, gullies usually cover a much smaller area than does cropland.

The third source of sediment is mass wasting such as landslides and mud flows. These types of erosion provide direct or indirect sediment supply to the stream channels. Slides or flows of the channel banks substantially increase downstream sediment loads. Indirectly, the sediment load can be increased by rill and interrill erosion of the surface exposed by the land slide as the result of removal of protective vegetative cover. In some areas of the country, particularly the coastal areas of the Pacific North West, land slide activity contributes most of the sediment load. These watersheds have some of the highest sediment loads in the United States.

3.1.1 Man's Influence on Upland Sources of Sediment

Man has had and will continue to have a dominant influence on the amount of sediment eroded from upland watersheds. Since sediment loads can have a dominant effect on channel stability, it is important to recognize the areas of influence and the magnitude of change that is possible. Man's activities that influence sediment sources can be grouped into seven categories (Guy, 1974). These are agricultural tillage, domestic animal grazing, highway construction and maintenance, timber harvesting and related activities, mining, urbanization, and recreational land development. Agricultural tillage is the activity most likely to influence channel conditions in the Great Plains and humid regions of the country because of the large percent of the area under cultivation. The land use in large sections of the country has and will continue to change. In the

late 1800's and early 1900's, large areas of the country were intensively farmed without conservation practices. Many regions of the country, such as those with easily eroded soils in Mississippi, Oklahoma, Texas, Tennessee, and Iowa, large areas were devastated by gullies. During this period, partial deposition of heavy sediment loads filled the downstream channels creating wide flat flood plains with very small channels and high water tables. As the land was abandoned, gullies gradually healed and the sediment loads were reduced. In some areas such as the Yazoo Basin in Mississippi, tree planting efforts were very effective in reducing erosion because of the vegetative cover and the surface mulch from leaves and needles. This led to much lower sediment loads, and the channels began to enlarge again creating new channel stability problems (Bowie, 1980). At the present time, the price of agricultural crops such as soybeans is causing more land to be placed into rowcrop production. These types of activity and the massive effect they can have on channels in certain sections of the country point to the need to consider the susceptibility of a region of the country to extensive changes. In the 1960's and 1970's, concepts of conservation tillage were introduced and are growing in application. In general, these practices reduce tillage or change farming operations, and minimize considerably the period of time that the soil is exposed. Over the next few decades such practices could lead to considerably reduced soil erosion rates and consequent changes in channel conditions. Many aspects of erosion from agricultural land are described in numerous articles in "Soil Erosion:Prediction and Control," published by the Soil Conservation Society of America in 1977 and "Present and Prospective Technology for Predicting Sediment Yield and Sources," published by USDA, Agricultural Research Service-S-40 in 1975.

The stocking rate of animals can significantly increase erosion rates of rangeland if not properly managed (Gifford and Hawkins, 1978). In forests, improper protection of logging roads, skid trails, channel crossings, etc. can lead to large sediment loads (Megahan, 1975). Strip-mined areas, construction sites and gullies developed in timber or agricultural land can yield up to 300 tons/acre if not treated, whereas normal rates of erosion from agricultural land range from almost nothing in good range and timber land to 100 tons/acre on poorly managed cropland.

In the next few years, we are likely to see significant changes in soil loss from agricultural land as grass barriers, conservation tillage, and terrace or grassed waterway construction programs and related practices are placed on the land to improve the quality of water.

3.1.2 Influence of Climate on Upland Sources of Sediment

Climate is another factor responsible for wide ranges in sediment yield. In large storms, excessive quantities of water from the watersheds can increase the ability of a channel to carry sediments, and massive erosion of the main channels can occur. The duration of the flood is also important. Flows that change rapidly are less likely to create bank erosion problems than long sustained flows that can saturate the banks and lead to vegetative kills and increased mass failure of the banks. The sequence of events, is possibly as important as any other factor. A stream channel could possibly remain in a relatively stable condition for many years, even withstanding a major flood event. However, if it should sustain two major events in a short period of time, without opportunity to heal between events, erosion could be massive enough that instability could develop that would lead to complete deterioration of the channel system. Even extremely dry conditions can lead to problems. For example, the dry conditions of forest and timber land lends itself to the possibility of forest fires that can completely denude the landscape. Heat from the fire removes organic matter from the soil, making it more susceptible to erosion. This, combined with the fact that the protection provided by the canopy has been lost, may lead to extremely high erosion rates until revegetation occurs. Drought periods can also cause vegetation to die, especially in arid or semi-arid areas. Then when rain does occur, large quantities of sediment are carried from the watersheds.

3.2 CHANNEL ASSOCIATED SOURCES OF SEDIMENT

As the size of a watershed increases to the point that it has a significant channel system, then the channel itself can contribute to the total sediment load. Both the banks and the bed are sources of sediment. As discussed earlier, the erosive power of the flowing water, the composition of the bank and bed materials and the vegetative cover influence the contribution from these sources.

In alluvial channels, the banks and beds are composed of the same material as that in transport, and the flowing water can change its channel

by meandering or braiding. If the banks are more resistant than the bed, entrenchment of the channel may occur. If local geologic conditions provide a resistant bed, lateral migration may occur. In upland areas of northern Mississippi, many channels have clay beds with lenses of sand below the clay. Many of the streams are experiencing down-cutting which exposes the sand strata, and the channels rapidly degrade until a new equilibrium is established. Massive channel bank failures result from this down-cutting. Both the banks and the sand in the beds provide a seemingly unlimited source of sediments. Frequently, the sources of sand from the beds are hidden because potholes that may be sediment sources during high flows are filled with sand from upstream during periods of low flow and are not evident. Thus, careful investigation of the channel system is necessary to evaluate fully the contribution from channel banks and bed.

If the channel banks are of a cohesive nature, individual particle removal cannot be calculated by considering only the erosive properties of the water. A large number of properties of the material (Partheniades, 1971; Grissinger, et al., 1980) are also significant. Even though erosion rates may be related to physical properties of the bank materials, the channel morphology limits, to a great extent, the ability to use these relations in field situations. In regions of the country where channel deterioration is occurring in cohesive bank materials, it is most likely caused by mass wasting, that is gravity-related bank failure rather than failure associated with hydraulic forces, even though the hydraulic forces are responsible for the removal of the debris. Typical modes of bank failure are associated with individual valley-fill stratigraphic units. The distribution of the stratigraphic units is predictable both within and between watersheds. This predictive capability results from paleoclimatic control of the depositional and erosional systems responsible for the stratigraphy in the banks. Thus, by using a systems approach it is possible to predict the types of instability of channel banks in cohesive materials (Grissinger et al., 1980).

A variety of other channel related activities or events can also provide downstream sources of sediment.

1. Debris dams lodged against bridges or other obstructions can cause bank erosion and even channel avulsion.

2. Failure of the bank at one point can cause trees to slide into the river diverting the flow against the opposite bank and further eroding the channel system.
3. Erosion of the outside of bends and accretion of materials on the inner bank will slowly change a channel.
4. Natural or man made cutoffs or massive landslides that block the channel, can also cause avulsion.
5. Channel modification can lead to degradation of the bed and make the channel wider.
6. Dredging operations can cause bank failure and, in extreme cases, cause spoil material to be eroded and placed back in the stream system.
7. The mining of gravel and sand can change the stability of the system due to removal of materials which are an integral part of the transport system. This leads to possible increased bank and bed erosion downstream. It also tends to remove the natural armoring material that may be responsible for channel stability.

4 CHANNEL STABILITY AND EROSIONAL PROCESSES

Processes responsible for erosion of stream banks can be interpreted either in terms of the mechanisms and forces involved, or in geomorphic terms. The proper interpretation of a channel instability or erosional problem requires an evaluation from both perspectives. If we look at it only in terms of the forces involved, we view any form of bank erosion as some form of imbalance and try to prevent it. However, in geomorphic terms, we recognize that most channel systems, even those in balance with their inputs of water and sediment, are going to experience erosion of their banks as they adjust to their changing loads. If the adjustment bcomes excessive and we must attempt to control it, we must look at the specific processes responsible. In the following sections, both interpretations are discussed.

4.1 TYPES OF STREAM BANK AND STREAM BED EROSION AND FAILURE

The following discussion of streambank erosion and failure is a slightly modified classification described by the American Society of Civil Engineers and presented by Keown, et al. (1977).

4.1.1 Erosion (fluvial entrainment) of Noncohesive Materials from the Bank, Bed, and Toe of Channel Banks

Previous discussion of channel bendways showed how secondary currents in a bend cause deep scour holes to develop on the outside of channel bends. Prasad and Alonso (1976) discussed the distribution of shear forces along the bank and bed of an alluvial channel with the bed in motion. Although of a theoretical nature, this study showed that extremely high shear forces can be expected at the toe of the bank if much of the bed is in motion, as may be the case in fine sand bed alluvial streams. Both secondary currents and bed motion concentrate forces at the base of the channel banks and can cause failure. Erosion of material at the base of a slope causes the banks to be both steeper and higher, thus reducing their structural integrity.

Stream channels that are unvegetated are subject to erosion by flow of water that generates a shear stress on the bed and banks. The gradual erosion of this material from the banks, even in straight reaches, is caused by the same forces that cause erosion of material at the base of a channel bank. The only difference is that the forces responsible for the shear stress may be developed in a different manner.

In order for the bank or bed materials of a channel in noncohesive materials to be in equilibrium, the boundary material must supply an internally derived, equal and opposite shear stress. The forces acting on a particle of bed material over which a fluid is flowing are the submerged weight of the particle, the lift force, and the drag force. These forces are shown in Figure 10 for laminar and turbulent flow. The symbols used in the expressions are as follows:

Drag force, F_d, laminar flow:

$$F_d = \tau_o C_2 d_s^2 \tag{21}$$

in which τ_o is the bed shear stress, C_2 is the form coefficient for the effective surface area of a particle, and d_s is the characteristic diameter of the particle.

Force due to gravity, F_g, in laminar flow:

$$F_g = C_1 (\Upsilon_s - \Upsilon) d_s^3 \tag{22}$$

in which C_1 is a form coefficient, Υ_s and Υ are the specific weight of the sediment particle and water respectively.

Lift force, F_L, in turbulent flow:

$$F_L = C_1 C_3 d_s^2 \frac{\rho U^2}{2} \tag{23}$$

in which C_1 is the lift coefficient, C_3 is a form coefficient related to the effective surface area of the particle in the direction of the lift force, ρ is the density of water, and U is the velocity of the flow near the particle.

Drag force, F_d, in turbulent flow:

$$F_d = \tau_o C_2 d_s^2 \tag{24}$$

in which the terms are described above.

Force due to gravity in turbulent flow is the same as in laminar flow:

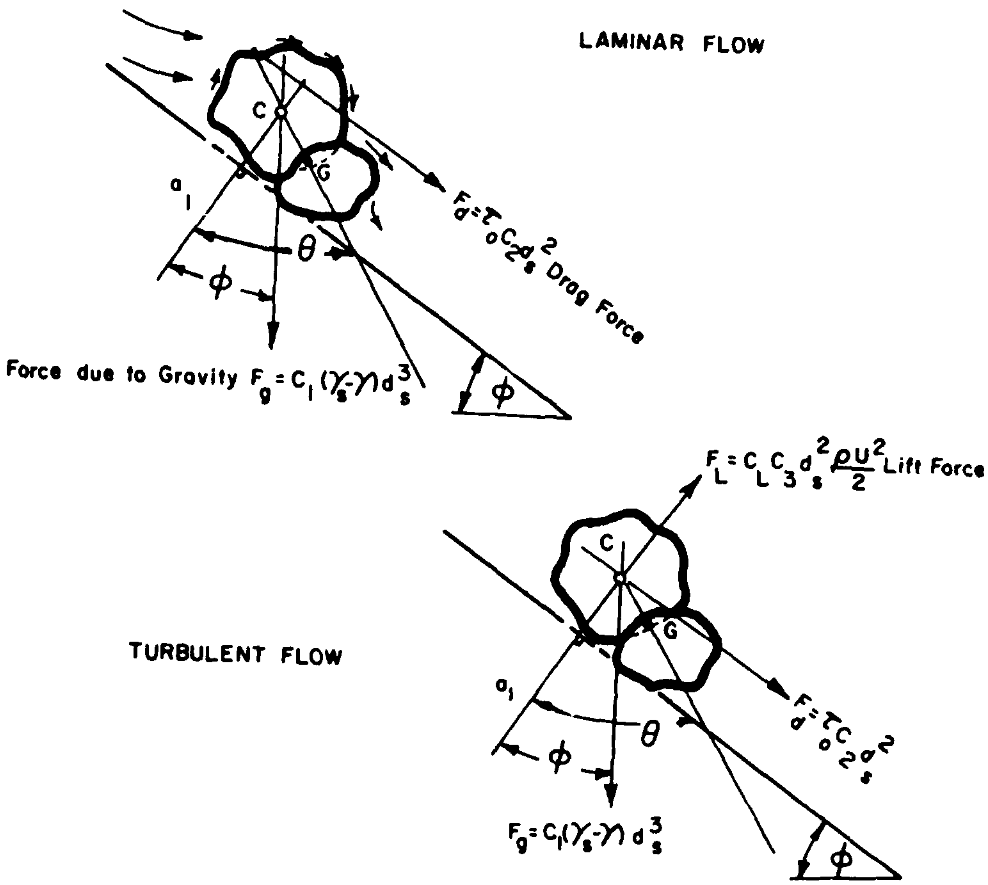


Figure 10 Forces acting on a submerged particle (After Simons and Sentürk, 1976)

$$F_g = C_1 \ (\Upsilon_s - \Upsilon) \ d_s^3 \tag{25}$$

in which the terms are described above.

In most practical cases, the moment of the forces about the point G for both laminar and turbulent flow at the beginning of motion simplifies to (Simons and Sentürk, 1976, pages 402-403):

$$\frac{\rho U_{*c}^2}{\Upsilon_s' d_s} = f \ (\frac{U_{*c} d_s}{v}) \tag{26}$$

in which U_{*c} is the shear velocity at the threshold condition, $\Upsilon_s' = (\Upsilon_s - \Upsilon)$, v is the kinematic viscosity of the fluid, and the other terms are as defined above.

Since Equation 26 is implicitly true for either laminar or turbulent flow, the difference in the equations for the two types of flow, is in the form that the functional f takes. The lift force (positive, negative, or zero) also influences the functional form of f.

Many experimental and theoretical solutions to the initiation of motion have been proposed. The Shields diagram is the best known. Simons and Sentürk (1976, pages 408-417) describe this and some of the other solutions. An understanding of them is basic to many geomorphic and hydraulic problems such as local scour, slope stability, stable channel design, and sizing of riprap.

When the concept of initiation of motion is applied to a particle on a stream bank, the resulting force on the particle, F_1, reduces to

$$F_1 - \sqrt{C_2^2 \ \tau_o^2 \ d_s^4 + W_s^2 \ \mathrm{Sin}^2\theta + 2C_2\tau_o d_s^2 W_s \ \mathrm{Sin}\theta \ \mathrm{Sin}\lambda} \tag{27}$$

and the restoring force, F_2, is:

$$F_2 = W_s \ \mathrm{Cos} \ \theta. \tag{28}$$

The natural angle of repose of the material is ϕ which is defined from:

$$\tan \phi = F_1/F_2. \tag{29}$$

In the above expression, W_s is the submerged weight of the particle, ϕ is the bank angle, λ is the flow angle and the other terms are as defined previously.

The expression for F_1 was developed without consideration of the lift force. However in practical terms, the effect of the lift force is considered in arriving at values of the empirical coefficients in the equations. In recent studies by Yen (1975) and Parker (1979), the fluid life force is represented by separate coefficients.

The above expressions and many others have been developed to size riprap. Simons and Sentürk (1976) describe many of these including those of the Corps of Engineers, Bureau of Reclamation, the ASCE Task Committee, the California Division of Highways and the Bureau of Public Roads. They also provide a theoretical analysis for the design of a stable channel. However, this analysis does not give an exact solution that can be used to estimate bank erosion, because the effects of other forces, such as cohesion, surface irregularity, vegetation, etc. cannot be included. Simons and Sentürk (1976) suggest that there are two methods of designing stable channels, (i) the method of maximum permissible velocity and tractive forces; and (ii) the method based on field experiments. They show by examples both the method of maximum permissible velocity by Fortier and Scobey (1926) and others; and the method of critical shear stress patterned after Lane (1953). Empirical relations such as those of Lacey (1929) are also discussed with examples.

The erosion of material f~om bed and banks of a stream channel can be either local scour like t se. at the base of piers and dikes or at obstructions such as chutes and drops; or the erosion can be extensive such as the banks in bendways or general scour of the entire river bed. The latter is considered as degradation and is particularly noticeable below diversion dams or in river reaches with extensive land use change that

results in a lowering of the sediment loads. Little information is available on the depth of scour in bendways, however it is discussed in Appendix A. The subject of local scour around piers, bridges and hydraulic structures is discussed by Coleman (1971), Laursen (1952, 1960, and 1963), Vanoni (1975) and Neill (1973). Simons and Sentürk (1976) also discuss local scour extensively.

Streambed degradation or aggradation has been discussed extensively by numerous authors. In the last few years, more refined sediment routing techniques have made it possible to predict the movement of sediment by particle size distribution. This has enabled us to calculate degradation, armoring and aggradation of stream systems.

4.1.1.1 Particle Segregation and Armoring of Sediment Mixtures: Conditions of uniform grain size are extremely rare in the field, and the effect of natural size gradation on the stability of alluvial channel material has been well recognized during recent decades. In the headwaters of natural rivers there are many grain sizes, including those the river can carry downstream under extreme flood conditions. These large grains are usually found dispersed along the river bed, and under non-flood conditions tend to form a natural armoring of the bed while the finer material washes out. This was clearly recognized by Lane and Carlson (1953) in the course of their study of different reaches of the irrigation canals in the San Luis Valley of Southern Colorado. These were very stable canals constructed in the alluvial fan deposited by the Rio Grande River. Based on their observations, they proposed the following Shields-like parameter to determine the critical shear stress, τ_c, below which the armor coat becomes strong enough to stabilize the bed

$$\frac{\tau_c}{(\Upsilon_s - \Upsilon)d_{75}} = 0.05 \tag{30}$$

However, a number of stable canals still in operation have values of this parameter considerably higher, up to about 0.08.

Harrison (1950) was probably the first to make a systematic laboratory study of the process of particle segregation leading to bed armoring. He duplicated the process observed by Lane and Carlson in the field and, in addition, he noticed that the particles armoring the bed were always one particle in thickness, covered less than one-half of the bed surface, and

were arranged in a shingle pattern. These observations were confirmed by Livesey (1965) downstream from the Fort Randall Dam on the Missouri River. Based on limited measurements of the bed surface texture, Harrison (1950) proposed using Einstein's bed load parameter ψ_*, to identify armoring conditions. Harrison stated that, for a given flow condition, $\psi_* = 27$ defines a unique sediment size below which there would be movement and above which there would be no movement. However, this is quite contrary to the results of Lane and Carlson (1953) and Gessler (1967) who found that in stable armored channels smaller sizes contained in the original distribution were found among the larger particles forming the armoring layer. From these observations the latter concluded that the process is probabilistic in nature, namely, that armoring depends on the statistical characteristics of the turbulent tractive forces, and also on the location and orientation of the individual grains. Gessler (1970) suggested that a stability coefficient for sediment mixtures be defined as

$$\bar{q} = \frac{\int_{d_{min}}^{d_{max}} [q(\zeta)]^2 \, p_o(\zeta) \, d\zeta}{\int_{d_{min}}^{d_{max}} q(\zeta) p_o(\zeta) \, d\zeta} , \tag{31}$$

in which p_o is the density function of the grain size distribution of the mixture, and q(d) is the probability of the grain size d not to be removed. In this expression $\bar{q}$ represents the mean value of the probability for the armor coat grains to stay. Gessler also developed expressions for the grain size distributions of the armor coat and the moving material. From field observations in the San Luis Valley canals (Lane and Carlson, 1953) and some limited laboratory results, Gessler (1970) concluded that the minimum permissible value of $\bar{q}$ is 0.50, and for design purposes he proposed to increase the permissible value to $\bar{q} = 0.65$. More recently, Little and Mayer (1972) reported a laboratory investigation of channel armoring. From their measurements they developed an empirical formula relating the sediment properties of the original and armored distributions to the flow properties. The formula is

$$\frac{d_{ga}}{d_{go}\sigma_{go}} = 0.908 \left(\frac{\rho U_{*c}^3}{\nu(\Upsilon_s - \Upsilon)}\right)^{0.353} \tag{32}$$

where d_{ga} and d_{go} are geometric mean diameters of the armored and original sediment mixtures, respectively, and σ_{go} is the geometric standard deviation of the original mixture, U_{*c} is critical shear velocity and ρ is the density of the water. They also concluded that if the geometric mean diameter of the armored layer calculated from the preceding relationship is between the d_5 and d_{95} of the original material, the bed would armor for the given flow condition. The results of this study were compared with the size distributions calculated by the method developed by Gessler. The geometric mean diameter calculated by Gessler's method were consistently lower than the diameters measured by Little and Mayer, with an average difference of twenty percent.

The above studies are concerned with the stability of bed layers exposed to steady, uniform flows. In the last few years, more refined sediment transport models have made it possible to predict the unsteady movement of sediment by particle size and, in the process simulate the time evolution of the bed layer composition. This has enabled us to calculate the degradation, armoring and aggradation of natural stream systems. Models of this type have been presented by Bennett and Nordin (1977), Thomas (1980), and Alonso and Borah (See Appendix J).

4.1.2 Erosion of Cohesive Materials

The erosion of cohesive materials by flowing water must be analyzed by an entirely different procedure from that used for analyzing the erosion of noncohesive materials. The primary reason for the difference is that cohesive materials have a net attractive force between particles that is the resultant of several attracting and repelling forces. The forces can be many times stronger than that of gravity and may develop either directly between adjacent soil particles or between adsorbed water films and thin layers of particles that are dependent upon the soil-solution chemistry of the water.

The particles that erode from cohesive materials are both aggregate and discrete particles. The heterogeneous nature of the interparticle forces will cause the surface to erode in a very irregular pattern. The rates of erosion are functions of the temperature of the eroding water,

antecedent water content, rate of wetting, pore pressure, suspended sediment content, and chemical quality of the eroding water (Grissinger et al., 1980). In some studies, the vane shear, tensil and unconfined compressive strengths of the material have been related to stability of cohesive materials whereas in others these relations have not been demonstrated (Grissinger et al., 1980). Part of the discrepancy between studies may be due to the fact that erosion is a surface phenomenon and if the bulk properties just mentioned are not related to the surface properties then there may be little correlation with erosion rate. Surface soil-water-chemical interaction and degree of roughness may alter the relations between the surface and the interior of a cohesive material enough to cause the above discrepancies.

All of the above factors make the erosion of cohesive materials a very dynamic process with extreme spatial and temporal variability. Thus the erosion of cohesive materials is the least understood and the most difficult to quantify. The state of the art of erosion and deposition of cohesive materials is described by Partheniades (1971).

An alternative approach in efforts to quantify erosion of cohesive materials is a field approach which identifies the various bank failure modes. Critical conditions of bank instability are identified and subsequently evaluated by controlled studies. This alternative approach has three advantages (a) stability relations are simplified and the number of pertinent variables is greatly reduced, (b) relations between channel conditions and watershed properties are facilitated, and (c) the study results have predictive capabilities for application to similar systems (Grissinger et al., 1980). This approach is discussed further in Appendix E.

4.1.3 <u>Sloughing Caused by Weathering and Weakening of the Surface</u>

Most processes of weakening and weathering are associated directly with soil moisture conditions. These processes fall into two groups: those which operate within the bank to reduce its strength; and those which act on the bank surface to loosen and detach particles or aggregates. The first process concerns pore pressures, etc. and is discussed in the Section 4.1.4 on massive sloughing. This section relates to the removal of surface materials.

Quite frequently, high intensity rain storms are associated with strong winds. If a stream bank is bare and oriented in such a way that the wind can drive the rain on it, then any loose material will be removed by the splash of the rain drops. Normal processes of erosion will also remove material from the surface as runoff from the rain flows over and down the face of the bank.

Periods of wet and dry cycles not only affect the internal stability of a block of bank material, but will gradually loosen the bank material by reducing the granular interlocking and destroying cohesion. This loose surface material is easily eroded by flowing water as the stream rises, or it can be removed by the force of gravity, thus accumulating at the base of the channel bank where it is eroded by the flowing water. Freezing of water in the pores of the surface material heaves the soil particles apart and loosen tne bank materials in much the same way that wetting and drying does.

The rapid rise of water in a channel can cause material to flake or slough off the bank surface if the outer portions of the banks are fine textured and dry. As water infiltrates the bank, the surface becomes saturated and air pressures can build up along a surface normal to the bank face causing failure and thin flakes "pop" off.

In almost all cases, vegetation on the surface will reduce the rate of surface erosion by several orders of magnitude (Thorne, 1980). The protection is afforded both by the reduced velocity caused by the plants and by roots in the surface of the soil.

4.1.4 Massive Sloughing of Banks

In a poorly drained bank, positive pore water pressure can weaken the b[illegible] by reducing its effective strength. The most critical condition [illegible] during heavy or prolonged precipitation, snow melt or rapid drawdown following a high flow stage (Thorne, 1980). Even if no significant pore [illegible] are exerted, the stability of a bank will be reduced by [illegible] because of an increase in the unit weight of the material and a [illegible] strength. Cycles of wetting and drying are also [illegible] they cause swelling and shrinkage of the soil. [illegible] isolated blocks or peds of soil fabric [illegible]ks, and downslope soil creep.

Blocks are characteristically about 0.15 m in size. Cracks can also develop as a result of the removal of overburden or erosion of the bank surface. Water movement through the bank can leach clay materials from the soil, reducing cohesion. In stiff fissured clays interped cohesion can be effectively eliminated by leaching so that the soil behaves as a cohesionless material.

Perhaps the most important factor in the massive failure of stream banks is the stratigraphy of the banks. Tight cohesive layers can impede water movement and provide a surface for lateral water movement. Seepage along this plane significantly reduces resistance to failure. Depending upon their location in the banks, noncohesive materials of sand and gravel are easily eroded leading to benched or undercut channel banks.

The modes of failure are dependent upon the type of bank material. In noncohesive materials failure is not a function of bank height and takes place by the dislodgment of individual grains from the bank surface or by shallow slips along a plane or very slightly curved surface; see Figure 11-a. Deep seated failures are unlikely because the friction component of shear strength increases more rapidly with depth than does shear stress. High seepage pressures can lead to piping in the lower part of the bank and failure of the bank along a shallow plane. Thorne (1980) discusses the effect of particle packing density, particle shape, and pore pressure on failure and the stability of the bank slope.

In contrast to noncohesive banks where stability is independent of height, the stability of cohesive banks is strongly dependent on both the bank angle and height. Often failure occurs as a deep seated slip (see Figure 11-b) because shear strength generally increases less rapidly with depth than does shear stress. Depending upon the depth of the failure, the type of material and the slope of the bank; the failure surface can vary from nearly a plane to deeply curved sections (Thorne, 1980). On steep banks the failure surface, in most cases, is nearly planar and parallel to the bank surface or passes through the toe of the slope. As the bank angle becomes flatter, the failure surface usually becomes deeper and the surface is curved. In deep seated failures of shallow sloped banks, the principal stresses change with depth. This alters the orientation of the failure surface (Carson and Kirkley, 1972; Terzaghi and Peck, 1948) and a circular arc or logarithmic spiral approximates the failure surface.

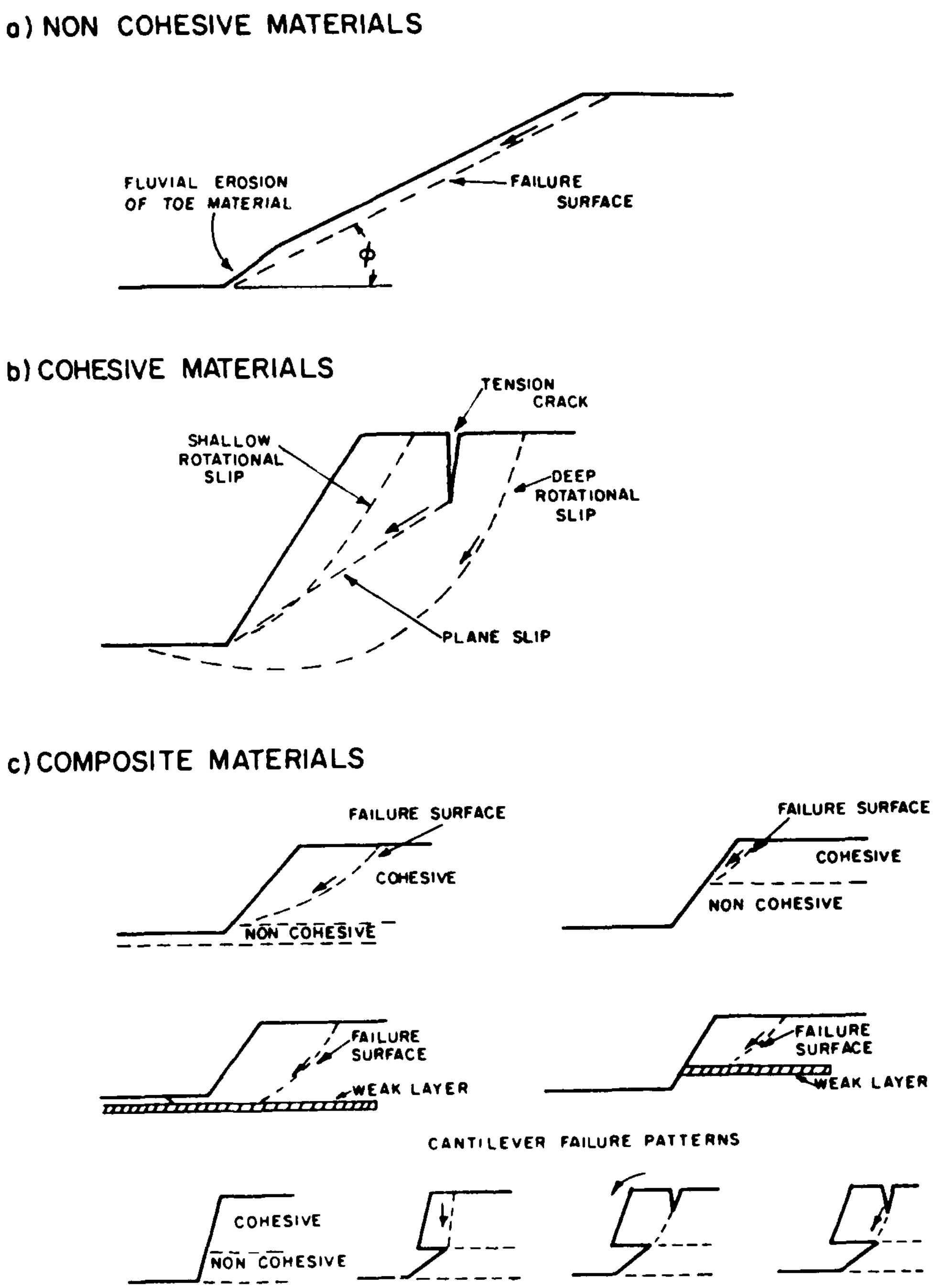


Figure 11 Typical bank failure surfaces (a) non-cohesive, (b) cohesive, (c) composite

In many cohesive soils cracks and fissures caused by desiccation and release of overburden pressure are found along the bank. These cracks can be long and parallel to the channel or they can isolate individual peds of material. These cracks and the form that they take should be considered in analyzing the strength of cohesive soils. Since the stability of cohesive soils depends upon the tensile strength of the soils, cracks become very important, especially in deep channels. Failure occurs when the cracks become deep enough that gravity and pore pressure forces exceed the resisting forces. If water can accumulate in the bank either as a result of seepage from above, seepage from adjacent fields, or seepage into the bank during high water conditions; it can build up pressure in the pores of the material, reducing inter particle friction and significantly reducing bank stability. Thorne (1980) discusses rotational, shallow, and plane slip failures with tension crack and pore water pressure effects.

The failure surfaces of composite banks are much more complex than those of either the cohesive or noncohesive bank. Erosion processes and failure mechanisms of composite banks reflect the nature of the bank materials and are combinations of those processes which operate on a single bank material. Common forms of failure are shown in Figure 11-c. They consist of deep rotational slip, plane slip and various forms of cantilever failure (Thorne, 1980).

Soil mechanics models used to determine the stability of cohesive, noncohesive and composite bank materials are presented in Chapter 7 of this report and in Appendix D.

4.1.5 Flow Slides (liquefaction) in Saturated Silty and Sandy Soils

Fine sands and silts are subject to failure by liquefaction. This occurs when a build up of water in the pores of the soil reaches a point that the pore water pressure balances the normal pressures between particles. At this point, the material loses its shearing strength completely and flows. This is a typical problem on the banks of fine grained noncohesive materials. The same pressures are responsible for increased pore water pressure of these materials as for others. That is, unusually large amounts of infiltrated or seepage water from rainfall or snow melt. If for some reason, the channel should sustain an unusually long period of high flow and then recede rather rapidly, saturated bank conditions could lead to instances of liquification.

4.1.6 Erosion of Soil by Seepage out of the Bank

Layered materials in the banks of a stream will concentrate seep water at zones above the most impervious layers. If the material above the impervious zones is uniform fine grained material with little internal strength, then at low flow conditions in the channel, when the head on the seep water is greatest, the quantity of seep water may be great enough to erode the material as it flows out of the bank. The result is the same as that for erosion of the material by water flowing in the channel; the development of cantilevered blocks of material that will eventually fail.

4.1.7 Erosion of the Upper Bank, Channel Bed, or Both Due to Wave Action

In wide channels that remain at one elevation for sustained periods of time either during flood flow or times of sustained flows due to regulation, wind can develop waves on the surface that will erode the banks and bed. The action is similar to that along beaches of the ocean or lakes. Waves created by boats can produce the same action, slowly eroding the bank until a bench develops that is wide enough to dissipate the wave action before it reaches the bank.

4.2 GEOMORPHIC PROCESSES OR MECHANISMS OF CHANNEL EROSION

In Chapter 2 general characteristics of the flow of water and sediments in alluvial channels were described. Their impact on channel pattern, width-depth ratio, sinuosity and other characteristics of the channel shape were presented. In this discussion, these geomorphic processes and mechanisms are described as they relate to channel erosion process of widening, deepening, sinuosity and migration. The geomorphic approach to study of channel erosion looks at the processes of erosion from a different perspective than that presented in the previous section of the report. In that section, various physical processes and forces responsible for erosion were described. These included fluvial entrainment of individual particles, sloughing caused by weathering of the surface, massive failure, and liquefaction. The geomorphic approach looks at channel erosion as a natural process of a system in dynamic equilibrium with its water and sediment load and channel make up, or as an attempt to change the shape of its channel to bring it into equilibrium.

In the discussion of geomorphic relations the qualitative relationship of Lane (1955)

$$Q_s d_{50} \sim Qs \tag{15}$$

was used to look briefly at sinuosity and channel configuration. This expression and equations 19 and 20 can be used to look qualitatively at changes that can be expected to develop in a channel as it responds to natural changes in climate and advertent or inadvertent man induced changes or regulation. In the following sections of the report, possible changes in width, depth and sinuosity of the channel will be considered in light of typical situations that lead to physical changes in the channel system.

4.2.1 Channel Changes Resulting from a Change in Flow Rate

If flood flows in a channel are reduced by land use changes or the construction of reservoirs, the river no longer needs a channel of its former size, and a gradual reduction in size will take place. The rate of reduction depends upon the type of stream channel. Armoured gravel bed channels, typical of those below large dams, may take a very long time to adjust. Gravel bed channels with numerous mid-channel bars can show significant changes in periods of one to two decades as the bars, no longer submerged, become vegetated trapping additional sediment. Gravel bars in the Peace River in British Columbia showed 10 to 20 cm of sandy-silty soil trapped in poplars and willows just 12 years after regulation (Kellerhals, 1980). Incised channels in fine grain materials respond to decreased flow rates by trapping silt and clay in vegetation lining the banks and can show very significant changes in relatively short periods of time. Channels of Sandstone Creek in Oklahoma went from a rectangular sand bed cross section to a parabolic shape in 10 to 15 years following regulation from flood detention reservors (Bergman and Sullivan, 1963).

An increase in the volume of flow from interbasin transfers is becoming more frequent. In general the channel response would be an increase in its size. In gravel bed channels, the higher velocities would disrupt any armor that may have developed under the previous regime and the channel would degrade until equilibrium is reached between the velocities and armor of the new regime. Kellerhals (1980) describes the response of two Canadian streams to interbasin transfer. In one channel the river widened its channel and straightened its course, thus increasing its slope

and flow carrying capacity. In the other stream, the channel degraded until it was controlled by bed rock sills. The intervening reaches, between rock sills, were straight with a gravel surface and incised 5-10 meters below the old channel floor.

Sometimes land use changes or regulation do not change the volume of water, but do change the distribution of flows along the channel. Normally, flooding along the main stem of a river is in phase with flooding in the tributaries. Under these circumstances, the tributaries are in a backwater situation. However, if reservoirs are constructed in the basin, then flood flow from tributaries downstream of the reservoirs may be out of sequence with that in the main channel and flows could enter the main channel with much higher velocities than normal. This could lead to rejuvenation of the tributaries with increased sediment loads and bank instability. It is also possible that head cuts could develop in the tributaries. In the main channel the increased sediment loads would be deposited because of the reduced flood flows and carrying capacity. This phenomena has been observed in tributaries of the Yazoo Basin below the major flood prevention reservoirs where deposition of material from tributaries has reduced the carrying capacity of the main channels. Kellerhals (1980) describes a similar response in tributaries of the Columbia River following construction of dams for power generation.

4.2.2 Channel Changes Resulting from a Change in Sediment Load

Land use changes can impose drastic changes in the sediment load to a stream system. In Mississippi, efforts to reduce erosion of the uplands of the Yazoo Basin included massive reforestation of large sections of the Basin. Reduced sediment loads resulted in a degradation of the stream systems both vertically and laterally as the channels tried to reduce their slope and, thus, their carrying capacity (Bowie, 1980). Cuffawa Creek which was a sand bed channel degraded extensively and sand, which had been temporarily stored in the channel, was removed. Hotophia Creek has also enlarged drastically as erosion of the channel progressed through the clay bed into nearly pure sand that underlies the clay. See Appendices A and E for further discussion of these effects. Stream channels can also reduce their slope by an increase in sinuosity, if they are not too highly incised, and become a meandering stream as sediment load is reduced.

Reservoirs and ponds reduce the sediment load in channels downstream. Depending upon the volume of water in storage and its temperature in relation to inflow, they can release essentially sediment-free water, or water that contains no coarse material but is high in fines. In sand bed rivers one of two things is likely to occur, depending upon whether reduced competence or reduced sediment supply is the most important. If reduced sediment supply is dominant, this leads to degradation until a stable, gravel-armoured bed is formed, or until the slope is reduced to a value which prevents further degradation. If reduced competence, the ability to transport suspended material, is dominant, then no change is likely to be observed if the flow is free of sediment. If the flow contains fine materials, the channel could aggrade or its size be reduced by deposition in vegetation along the banks.

Changes in land use can have the opposite effect on stream channels. It is possible for the economy to be such as to cause widespread changes in land use such as the planting of soybeans on land that should remain in grass or timber. This could lead to a situation similar to that in the late 1800's and early 1900's when much of the hill land in the eastern part of the country was farmed. This led to widespread erosion and very heavy sediment loads. Under these circumstances, the stream channels rapidly fill with sediment as the channels try to increase their ability to transport the material by increasing the slope. Recent trends toward use of timber in wood heating systems could lead to rapid and extensive deforestation, with subsequent increased erosional problems. In other channels, for example West Goose Creek in the Yazoo Basin, it is possible for a meandering channel to become braided or shallow as sediment loads are increased, providing more opportunity for overbank flooding and, thus, deposition of material. In gravel bed streams increases in sediment load generally lead to braided conditions and bank erosion.

4.2.3 Channel Changes Resulting from a Change in Slope

Meandering stream channels are frequently straightened as part of flood control programs. Also, natural cutoffs may occur. Both of these conditions lead to an increase in the slope of the channel upstream. These higher velocities lead to increased sediment transport and possible degradation of the bed, unstable banks and tributary instability. Depending upon the degree of meandering or channel slope, the channel

pattern could change from a meandering stream to a braided one with unstable river banks. Bed degradation could even take the form of a headcut through the upstream reach. Lowering of the channel at points where tributaries enter could also initiate a rejuvenation of the tributaries and knickpoint or headcut migration. The impact of knickpoint migration is dependent upon the channel stratigraphy. If the knickpoint exposes unconsolidated sands, then erosion could lead to massive bank failure as described in the first part of this Chapter. Also it is possible that the knickpoint could be large enough that it would make the banks so high that they would not be structurally stable and again massive failure would be experienced. These types of conditions exist at the present time in many sections of the Mississippi embayment. When this happens, the channels will continue to widen until debris accumulating along the banks is no longer eroded and remains to protect the banks. The width/depth ratio needed to provide that protection is a function of the flow and sediment load in the channel.

Downstream from a knickpoint or cutoffs increased flow rates and sediment loads created by the channel erosion upstream will lead to deposition, loss of channel capacity, and increased flood stages.

In the upstream reaches of large reservoirs, sediment deposition in the main channel and tributaries reduces channel slopes, velocities, and carrying capacities. This causes a change in the flooding frequency of the channels with more frequent overbank floods. This in turn can lead to changes in channel alignment as it attempts to adjust to new channel conditions.

In all of the previous discussions of the response of a channel to changes in flow rate, sediment load, and channel slope; the changes that take place are attempts of the stream system to come to a new dynamic equilibrium. In many cases, changes in one variable do not occur without corresponding changes in other variables. Under these circumstances, it is difficult to determine what the net result may be. Simons and Sentürk (1976) discuss with examples anticipated response of a channel system to engineering changes such as revetment, dikes and reservoirs. They also outline a series of steps to follow in river system design giving the types of data needed. In recent years, computer models have been developed that can also help answer some of the qualitative and quantitative questions raised in the previous discussion. Some of these models are described with examples in Chapter 7 of this report.

5 METHODS OF CHANNEL PROTECTION

Methods of protecting a stream channel or preventing a change in its location can be classified by the materials of which they are constructed, the general shape of the device, or according to their function or application; See Appendix C of Keown et al. (1977) for a glossary of streambank terminology. In the following presentation, classification is based on the function or application:

- Armor
- Retards
- Spur Dikes or Jetties
- Bulkheads
- Baffles
- Grade Controls
- Vegetation
- Geometric Alignment of the Channel

Keown et al. (1977) and the State of California Department of Transportation (1970) have given extensive discussions and references of channel protective devices. Charlton (1980) also has presented a recent review of literature related to methods of bank protection.

Armor, retards, dikes, bulkheads, baffles and some types of grade control have been used extensively in protecting areas of the stream bank and streambed. However, this report concentrates on a study of the causes of streambank instability and on methods to prevent instability rather than repairing or protecting the channel where instability shows up. In most cases, channel instability can be controlled by a combination of bed control and bank protection. However, most of these methods are so expensive that they are hard to justify. In this report, we are concentrating efforts on less expensive means of control and directing attention to grade control and combinations of vegetation and riprap toe protection. Perhaps the most effective means of bank protection is channel grade control. Obviously this cannot prevent meander migration, but it can be used to control much of the cause of channel instability. Appendix B is a detailed description of a minimum cost grade control structure. Vegetation in combination with a minimum amount of riprap or other toe protection may also be a cost effective means of bank protection. Appendix C discusses research on several combinations of vegetative and structural material for bank stabilization.

Following is a more general discussion of the various methods of protection according to their function or application.

5.1 ARMOR

Armor is the artificial surfacing of stream channel bed, banks or embankments to resist erosion or scour. Armor applied to a bank is normally referred to as revetment. These are the most common types of protective devices used, because they will almost always prevent erosion due to abrasion and scour irrespective of river gradient or velocity, if properly sized. It is essential to protect the toe of the revetment against local scour which can be as great as two and a quarter times the average depth of flow (Charlton, 1980). Toe protection is generally achieved by extending the revetment to the depth needed. It is also necessary to provide adequate filter material under the armor to prevent loss of material and provide a means of reducing seepage pressure. Revetment can be either flexible or rigid. Figure 12 shows a typical rock riprap revetment.

5.1.1 Flexible Revetment

Flexible revetment materials consist of rock riprap, tire mattresses, articulated and cellular concrete block, rubble and broken concrete, etc. These materials have an advantage over rigid types in that they can shift and settle without impairing or weakening the protection.

5.1.2 Rigid Revetment

Rigid revetment materials consist of such things as sacked concrete, grouted rock and asphaltic slope paving.

5.1.3 Other Types of Revetment

Other revetment surfaces being used include soil cement, sand cement in sacks, and cabled automobile bodies.

5.2 RETARDS

A retard is a bank-protection structure designed to reduce the velocity of water near the banks and induce sedimentation or deposition rather than erosion. Retards are permeable structures usually constructed parallel to realign a bendway to a more reasonable radius of curvature. Deposition behind the structures replaces material that has been lost. In some retard systems, as accretion occurs new piles are driven to raise the level of protection. Both the structure and deposited material cause a shift of the higher velocities toward the center of the channel and away

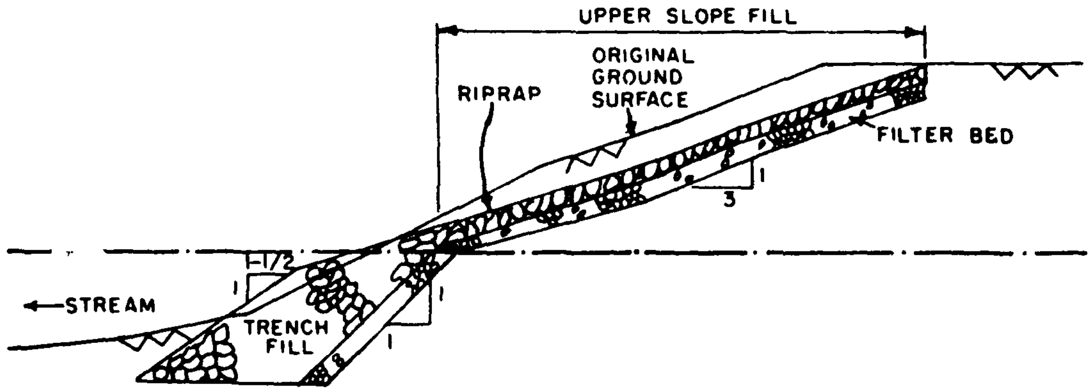


Figure 12 Typical rock riprap revetment

from the bank. There are many forms of retards but the most common are steel or concrete jacks, training fences of double or single lines of board fence and combinations of single or double rows of timber or steel piling and wire mesh fence. Sometimes the area between double rows is filled with rock or other debris. Figure 13 is a photograph of a typical training fence.

5.2.1 Fences

Fences are used to solve a variety of bank protection problems on low gradient systems. They may consist of a board and piling arrangement such as in Figure 13 or a series of wire and steel post fences, transverse to the flow, that are designed to either catch or bypass trash over a large area. Fences can also be used to divert the flow large distances. Sometimes brush, hay, or rock is piled between double rows if velocities are high and they must be reduced considerably.

5.2.2 Jacks

Jacks are frames, usually with three mutually orthogonal legs, joined at their midpoint. They are normally constructed of steel rails and cabled together and anchored in rows. They have been used extensively in the western part of the United States as training fences. They are particularly effective in trapping debris.

5.3 SPUR DIKES OR JETTIES

A spur dike, sometimes known as a hard point, is an elongated obstruction projecting into a stream to control bank scour by deflecting strong currents rather than inducing deposition along the bank. Normally spur dikes are impermeable structures but occasionally they are permeable to permit some flow through the structure to prevent the formation of eddies immediately downstream. In gravel bed streams, the spur dikes should be oriented nearly perpendicular to the flow or inclined slightly downstream. They normally extend into the stream past the point of maximum velocity in order to move the thalweg from its position, along an eroding bank to a more desirable alignment. The height and spacing of dikes is critical in determining their effectiveness. See Charlton (1980) and Keown et al. (1977) for more information. Figure 14 is a typical spur dike arrangement.

Figure 13 Training fence to reduce the velocity and induce deposition along an eroding bank

AD-A101 385 SOIL CONSERVATION SERVICE OXFORD MS SEDIMENTATION LAB F/G 8/8

STREAM CHANNEL STABILITY.(U)

APR 81 D G DECOURSEY

UNCLASSIFIED NL

2 OF 3

AD

A101385

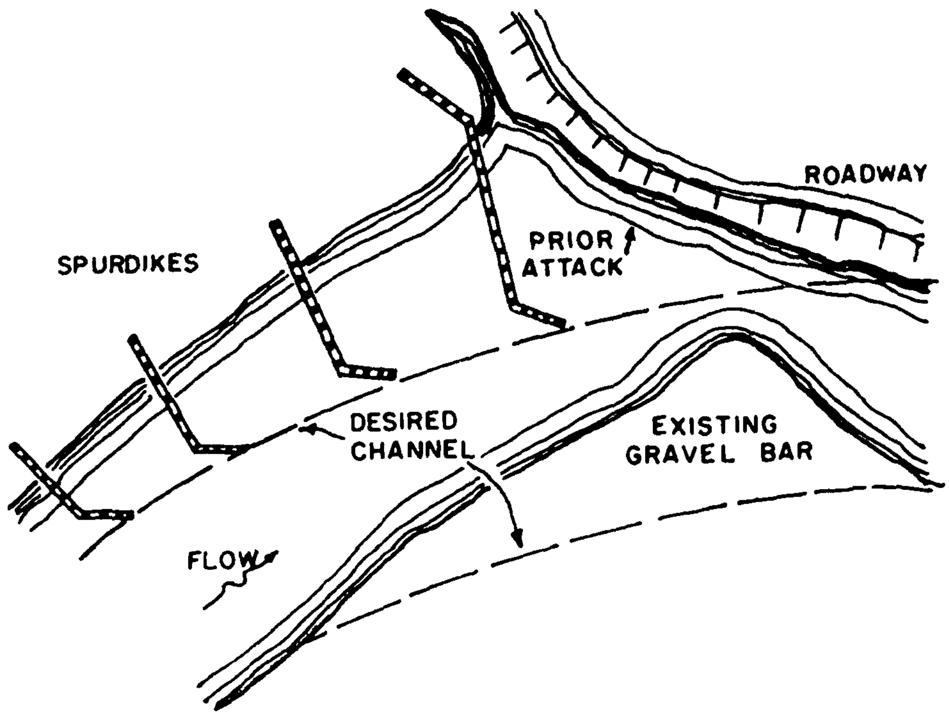


Figure 14 Typical spur dike arrangement (After California Department of Transportation, 1970)

5.3.1 Impermeable Spur Dikes

Impermeable spur dikes are usually constructed of rock, earth or sheet piling. Log or timber cribs filled with rock or other material are also effective.

5.3.2 Permeable Spur Dikes

Permeable spur dikes usually consist of single or double rows or braced piling. Jack fields can also be used as permeable spur dikes.

5.4 BULKHEADS

Bulkheads are steep nearly vertical structures supporting a natural or artificial embankment. Solid bulkheads are rather expensive but can be justified where valuable property or improvements are involved and the foundation is not satisfactory for the more inexpensive types of protection. Frequently, bulkheads or cribs are used for toe protection in combination with different types of revetment on the overlying banks. They can also be used for protection against mass failure such as described in Chapter 4. Thus, they serve two purposes, supporting an embankment and protecting it from erosion. As retaining devices, they should be designed by conventional methods for retaining walls, cribs and laterally-loaded piles. As armor protection against erosion they should be secure against hydraulic forces at their ends and toe. The most common types consist of timber piling, concrete or masonry walls, timber or steel sheet piling and various types of log or concrete cribs filled with rock or other materials. Figure 15 is a photograph of timber crib bulkheads.

5.4.1 Walls

The most common type of wall used as a bulkhead in streams is the wing wall on culverts or at abutments to bridges. These are usually made of concrete.

5.4.2 Cribs

Cribs are interlocking steel sections or logs used to build a stable mass at the base of a slope. Timber materials are the most frequently used because of availability.

5.4.3 Piling

Timber, concrete and steel piling are used for bulkheads depending upon penetration of foundation materials. High bulkheads must have deadmen or batter piles to counterfort or support the upper part of the bulkhead.

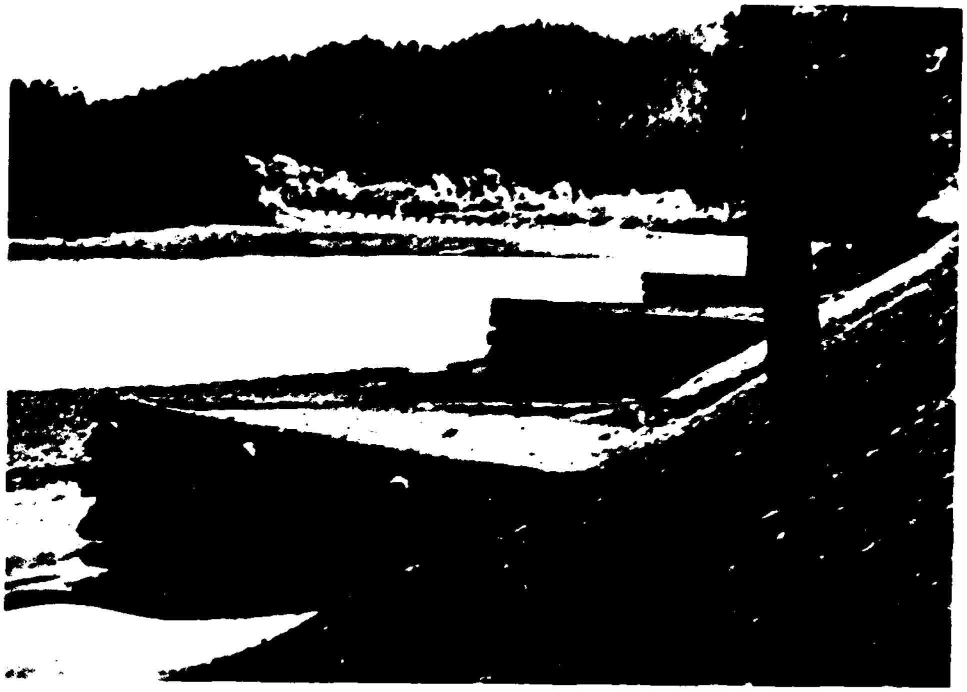


Figure 15 Timber crib bulkheads (After California Department of Transportation, 1970)

5.5 BAFFLES

A baffle is a pier, vane, sill, fence, wall, or mound built on the bed of a stream to deflect or check the flow. Training fences are the most commonly seen devices in this classification because they can be adapted to many conditions. Baffles are designed to control eddies and to guide or deflect the flow rather than reduce the velocity. Fences and small check dams fall into this category and are usually constructed of rock, concrete, timber, sacked concrete, filled fences, sheet piling, or a combination of the above. Figure 16 shows a training fence used as a baffle.

5.5.1 Training Fences

Training fences used as baffles are designed to control eddies along a bank and to deflect the flow away from the bank rather than to check its velocity. Fences are usually single, double, or triple rows of wire (sometimes filled) although they can be rock or earth dikes and wire bound rock sausages.

5.5.2 Check Dams

Check dams are an effective means of gradient or velocity control and may be constructed of concrete, timber, sacked concrete, filled fences, sheet piling or combinations of the above. They are discussed extensively in the following section.

5.6 GRADE CONTROLS

Degrading stream conditions produce high and steep banks that result in massive bank failures as described in Chapter 4. Under these conditions, bank revetment techniques are ineffective and many times fail because the bed has not been stabilized. Channel grade-control structures provide a means of eliminating or reducing channel degradation to tolerable limits enabling bank revetment techniques to be effective. The amount of fall permissible in channel grade-control structures is usually limited to 6 feet or less to avoid overbank flooding during extreme events. Thus, flow depths in most streams will be from 1 to 4 times the amount of physical drop in the structure.

A low-drop structure (see Appendix B for details) is defined as an hydraulic drop of magnitude H (difference in elevation between upstream and downstream channel bed) for a discharge, Q, and corresponding critical depth, Yc, such that the relative drop height, H/Yc, is equal to or less

Figure 16 Double row slotted fence used as a baffle on Hotophia Creek in Mississippi

than 1.0. Conversely, a high drop would be defined such that the relative drop height is greater than 1.0. Thus, a drop structure could function as a high-drop at low discharges and as a low-drop at higher discharges. A unique feature of a low-drop structure, without any auxiliary means of energy dissipation, is that an undulating hydraulic jump develops. Details of a low-drop structure, designed to minimize problems associated with an undulating jump, are presented in Appendix B along with detailed design criteria. Figure 17 shows a typical low-drop structure designed by these criteria and located on Perry Creek near Grenada, Mississippi.

5.6.1 High-Drop Structures

Connelly and Blaisdell (1954) present detailed design criteria for a high-drop, rectangular straight drop spillway and stilling basin. This design is applicable to relative drop heights, H/Yc, ranging from 1.0 to 15. The Soil Conservation Service has constructed many of the straight drop structures (now commonly referred to by SCS as the Type "C" drop structure) since 1954, ranging in physical drop heights up to 20 feet. Donnelly and Blaisdell (1965) later expanded the design criteria for the straight drop spillway stilling basins. Figure 18 shows a cross-section and plan review of the straight drop spillway (after Donnelly and Blaisdell, 1965).

Bradley and Peterka (1957) and Peterka (1964) present detailed design criteria for six different types of stilling basins for approach Froude numbers from 2 to 20. These would all be classified as high-drop structures. All high-drop structures use a combination of chute blocks, flow blocks and/or end sills in the stilling basin to reduce the length of the basin. If the length of basin is too short to dissipate the energy, excessive scour will occur in the downstream channel.

5.6.2 Low-Drop Structures

To the authors knowledge, there are no design criteria available in the literature for low-drop structures. The low-drop structures require a stilling basin and auxiliary energy dissipators because an undulating hydraulic jump is formed. A stilling basin 1.5 to 2.0 times the upstream channel bottom width is required. Either a baffle pier or baffle plate is used to break up the undulating jump by causing flow separation (turbulence) around the baffle. Figure 17 shows a field installation of the baffle pier and Figure 19 shows a field installation of the baffle plate. Both were constructed by US Army Corps of Engineers, Vicksburg

Figure 17 Baffle Pier - Perry Creek, MS

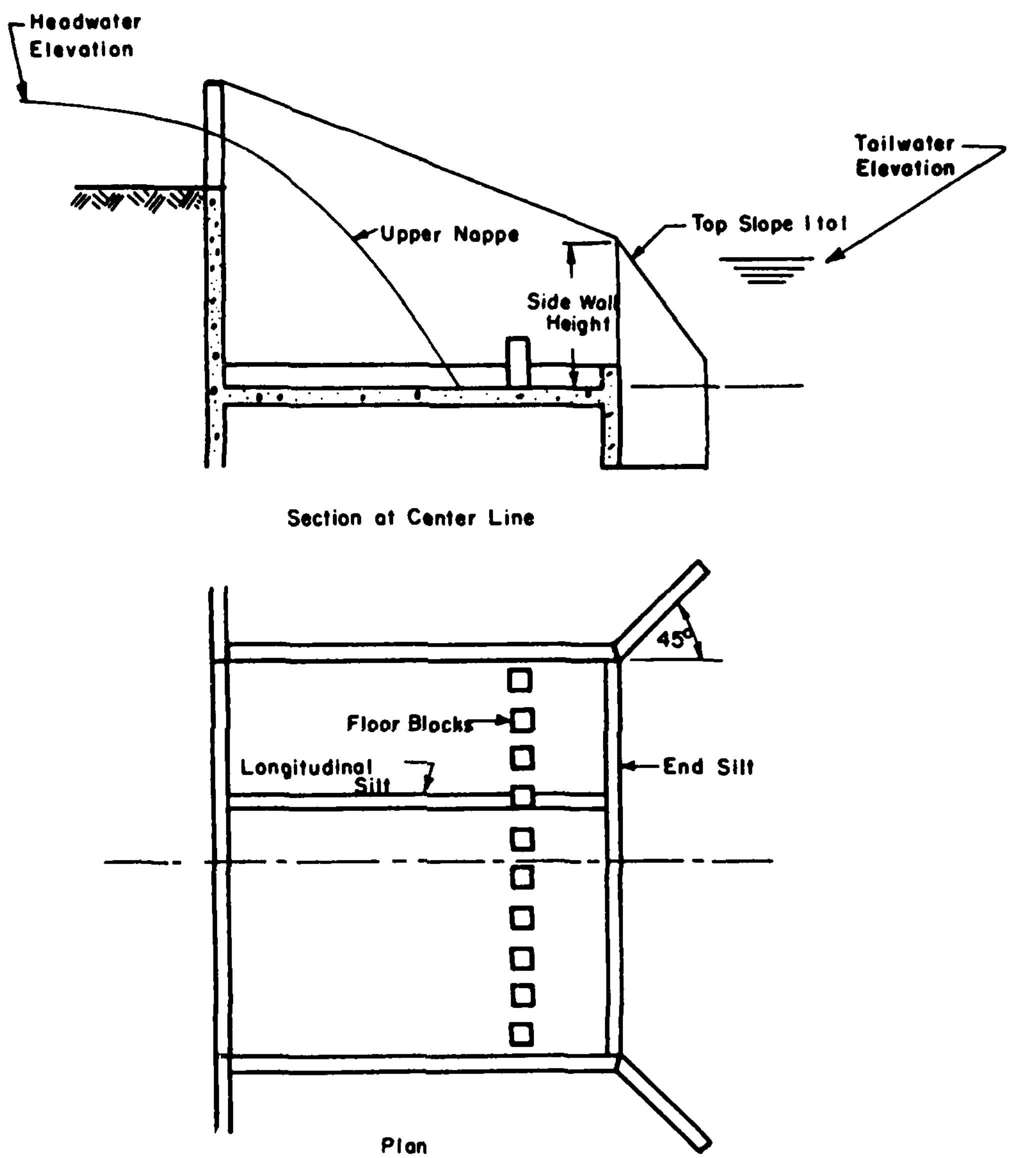


Figure 18 Straight drop spillway stilling basin

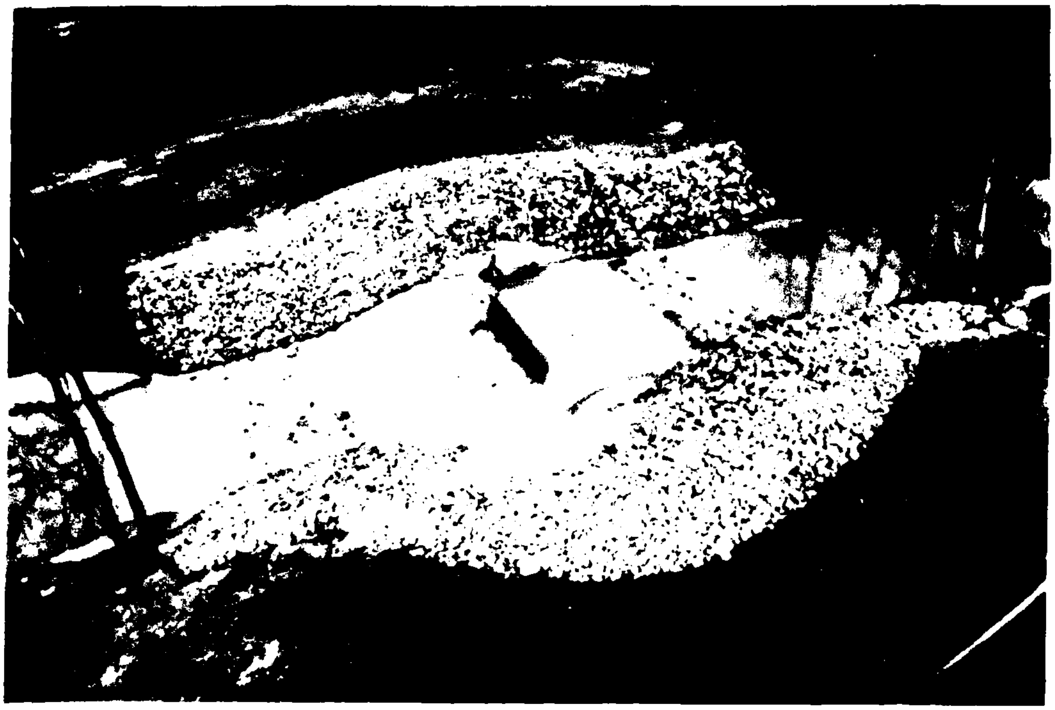


Figure 19 Baffle Plate - Tillatoba Creek, MS

District. These structures were designed to provide more economical structures than the straight drop spillway stilling basin which is normally constructed of concrete. The low-drop (4 feet of physical drop and a design discharge of 6000 cfs) as shown in Figure 19 cost approximately $140,000, many times less than a straight drop spillway of concrete. The type "C" drop structure does not have a baffle plate and hence will not destroy the undulating hydraulic jump when it is functioning as a low drop. This may cause excessive channel bed scour downstream.

5.6.3 Supercritical Flow Flumes

Low drop grade control structures have also been used to measure flow rates because they control the water level in the channel upstream. The use of supercritical flumes for flow measurement began in the late 1950's mainly in Colorado and Arizona. Many of the Western States have steep ephemeral streams which transport large quantities of sand, gravel and boulders during summer thunderstorms. The type of supercritical flumes used on Goodwin Creek watershed were first developed in conjunction with hydrologic studies on watersheds in Southeastern Arizona by the USDA Agricultural Research Service and were installed on the Walnut Gulch watershed. Hence, many people refer to this particular type of supercritical flume as the "Walnut Gulch Flume". However, the specific design is more like the Sante Rita Flume (Smith et al., 1981). Many problems were encountered with the flumes constructed on Walnut Gulch watershed. Among those were (i) extreme scour downstream from the structures (several structures were undermined and failed completely), (ii) deviating flow caused by entrance misalignment, and (iii) problems in sensing water level in the heavy sediment-laden water. A comprehensive paper on supercritical flow flumes for measurement of sediment laden flow is being prepared for publication (Smith et al., 1981).

The experiences of all USDA-SEA-AR personnel associated with previous work on the supercritical flow flume (personal communication) were considered in the design of the Goodwin Creek Supercritical Flow Flumes. Limited data was obtained from a 40:1 physical model, especially the geometry of the stilling basin and appurtenances for optimum energy dissipation.

The hydraulic design, based on a 100-year return period design storm, for each site was developed by Sedimentation Laboratory personnel and given

to U.S. Army Corps of Engineers, Vicksburg District, Design Branch, for structural design. Figure 20 is a view of Structure 3 on Goodwin Creek after completion and is typical of the other structures. A majority of the structures were completed in the Spring of 1980.

A description of the instrumentation at each site is given in Section 6.2. Design details of each structure are given in Appendices A and B. In Goodwin Creek these structures function both as grade controls and flow measuring devices.

5.6.4 Rock Lined Gradient Control Structures

A rock lined gradient control structure is a rock lined channel, both bed and bank, with a slope such that the flow through the structure at bank full design discharge will be subcritical. An average bed slope for a typical rock lined chute is 0.5 percent. Thus, for a channel bed to drop 4 feet through the structure, the chute must be 800 feet in length. Even though flow in the chute is subcritical, with relatively low velocities, huge quantities of rock make these structures extremely expensive and even prohibitive where rock must be transported considerable distances. The Soil Conservation Service developed this type of drop structure. It is described in a USDA-SCS Technical Release (1976).

5.7 VEGETATION

One of the least expensive means of bank stabilization is the use of vegetation. Both woody plants and herbaceous vegetation can play an important role in stabilizing and controlling channel bank erosion. Total costs of vegetative stabilization will generally be far less than structural methods, however, control of severely eroding channel banks may require a combination of vegetation and structural treatments. Structural measures most commonly used in conjunction with vegetation are armor and retards. The degree of success experienced in using vegetation with bank shaping and with no structural measures, or without bank shaping and without structural measures, is dependent primarily upon the composition of the bank and bed material, the degree of meander, bed stability, storm flow and velocity characteristics, and slope of the formed bank.

5.7.1 Vegetation in Conjunction with Armor and Retards

As previously stated, armor material used for bank protection is normally referred to as revetment. The revetment used in conjunction with

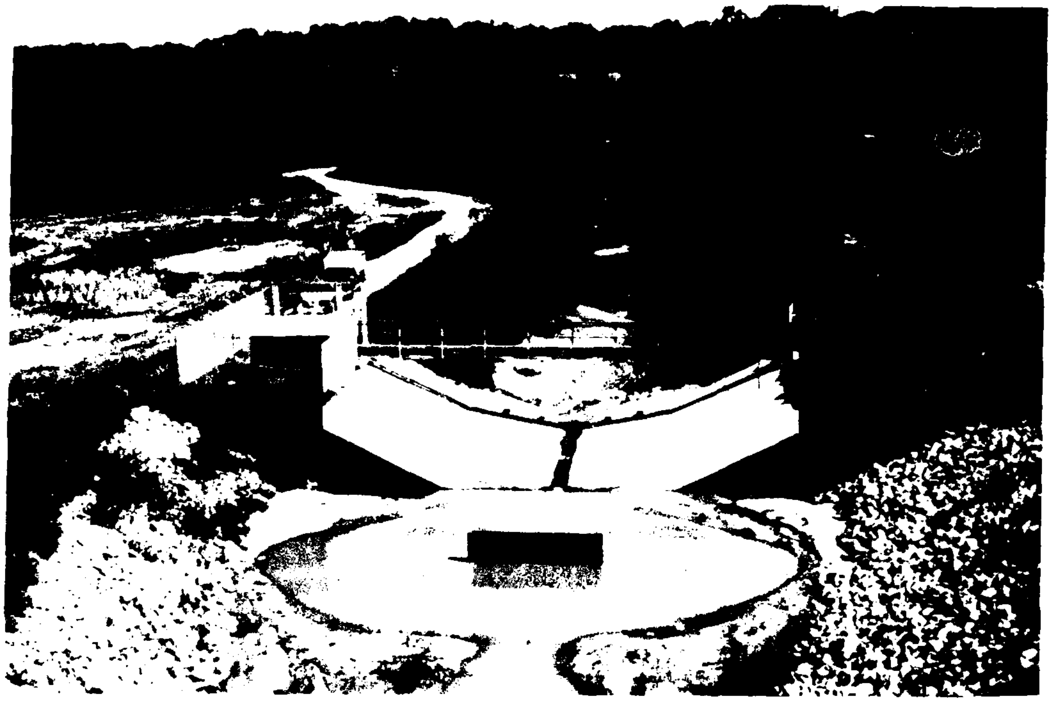


Figure 20 Supercritical Flow Flume - Structure 3 Goodwin Creek, MS

vegetation on formed banks may be riprap, cellular concrete blocks, articulated concrete blocks, etc. The remainder of the bank surface is planted to various species and types of vegetation. In conjunction with retards, woody plants are planted in the space behind and between the retard and channel bank. Satisfactory results can usually be expected with planting behind retards such as training fences, jacks, wire mesh fence, and riprap. Figure 21 shows riprap used as a retard in a channel bend with a growth of woody plants between the retard and the channel bank.

5.7.2 Vegetation with and without Bank Shaping and No Structural Measures

Vegetating formed bank slopes without the use of structural measures is usually limited to agricultural type waterways or small channels with stable beds and a fairly low gradient. Under most conditions, bank slopes should be no greater than 1:2. Better results will be experienced using slopes 1:3 or flatter. If bank undercutting or unstable bed conditions are evident, bank shaping without the support of structural materials is questionable. Vegetating without bank shaping and no structural measures is usually limited to woody species. Native species such as willow are the easiest to propagate. The degree of success is determined to a large part by the amount and type of material deposited along the bank toe line and by whether or not planting is attempted along a concave bank. The greatest problems exist along concave banks, and these are the most difficult to vegetate without retards.

5.8 GEOMETRIC ALIGNMENT OF THE CHANNEL

Since many channel stability problems come from attempts of the channel to adjust itself to a wide range in water and sediment loads, structural measures such as described above may not be satisfactory. This is because they do not address the problem of maintaining a channel with the carrying capacity necessary to cover the range needed. Winkley (1980) describes problems in maintaining the channel of the Mississippi for navigation purposes. He shows, by studying the characteristics of the channel in different reaches, that a proper degree of sinuosity is needed to give the river the latitude it needs to transport and store sediment over the range of flow conditions it experiences. Perhaps a very effective means of protecting many other channels is to study stable reaches and based on those findings adopt a channel geometry and sinuosity that will

Figure 21 Woody plants used in conjunction with a riprap retard

maintain itself and store excess sediments on its bars during low flows, and transport this material during high flows when the main thread of the flow cuts across the point bars.

6 IDENTIFICATION OF THE PROCESSES RESPONSIBLE FOR CHANNEL INSTABILITY AND POSSIBLE SOLUTIONS

Previous chapters of this report have dealt with the changing state and deterioration of alluvial channels and how this lead to the Section 32 Program of study of streambank erosion. The characteristics of rivers and their morphology, watershed processes and their impact on the channel system, physical and geomorphic processes of bank erosion and methods of protection have been presented as background for a general discussion of the processes responsible for channel instability and possible solutions.

Channel instability can be divided into three broad classes depending upon the degree of instability. The least severe and easiest to correct is point instability in an otherwise stable channel. Correction may or may not be expensive, depending upon the nature of the problem site. Examples of point instability are: (i) bank erosion caused by the deflection of flow from a snag, fallen tree or other obstruction and (ii) bendway erosion caused by the natural migration of meanders. Reach instability is more extensive than point instability and the problem areas extend through more than one bendway. The instability could be caused by weak or unusual conditions leading to failure of bank materials.

Reach instability can also be caused by locally excessive sediment loads or the effects of structures such as beaver dams or diversions. The most extensive problems are associated with total channel system instability such as may be caused by major land use change, loss of downstream control, and stratigraphic structural instabilty in the banks and beds. In the following parts of this chapter we will describe these three broad classes of channel instability and methods to identify the processes responsible for the instability.

The concept of a stable channel as opposed to an unstable one is a matter of the degree of instability. Since rivers or streams are dynamic, they are always changing. Even in periods of stability in external or internal forces, the channels will be changing, but the loss of banks in one reach will be offset by an equivalent bank development in another. Therefore, stability from an economic point of view is subjective. If the loss of bank is enough to be of concern to the landowner, is producing sediment loads that create problems downstream, or the channels are in a state of rejuvenation, then they are unstable and corrective steps are justified and advisable.

6.1 PRELIMINARY SURVEYS AND SOURCES OF INFORMATION

Before studying a specific problem site or reach of channel instability, a general evaluation of channel conditions in the region should be conducted to determine the extent of instability. A field tour of the problem area by automobile and/or air should be supplemented by field reconnaissance of a representative sample of channels of various size (stream orders). Quite frequently bridge crossings give a biased impression of channel conditions as they can create either a false sense of stability or instability depending upon the degree of control the bridges have on the channel. Therefore, "windshield tours" should be supplemented by field reconnaissance.

Discussions with elderly residents can frequently help greatly in assessing the recency of bank failure, out of bank flooding, crop damage, type of failure, depth and width of the channel in previous years, channel location, history of channel construction and channel clean out, and previous land use. Similar types of information and records of flood flow sediment deposition, crop damage, etc. can be obtained from federal, state, and local agencies such as the Soil Conservation Service, the U.S. Geological Survey, the State Department of Agriculture, the Agricultural Stabilization and Conservation Service, and Flood Control and Drainage Districts. Federal, State and local libraries also have useful information in the form of records of floods, droughts, construction projects and related types of information in old newspapers. Federal Archives may have copies of construction contracts, old cross sections, flood elevations and profiles. Similar types of information may be available from records of construction and consulting engineering firms.

Aerial photographs of most sections of the country are available on a periodic basis dating back to the 1930's. These are especially helpful in studying the history of channel change. By using stereo pairs it is also possible to estimate channel depths accurately enough to study the width-depth ratios of the channels in the region of interest (Ethridge, 1979).

In the last few years various mathematical models have been developed that can also provide guidance in assessing channel stability problems. These models are discussed in more detail in Chapter 7 and in Appendices D, I, J, and K. They consist of bank stability models based on the soil

mechanics properties of material in the banks and also of several hydrologic models. The hydrologic models suggested as being helpful consist of two general hydrology-sediment yield models, and a sediment transport model. A fourth hydrologic model, which requires more development to be used effectively, is a two dimensional finite element model for studying specific sites. The general hydrology-sediment yield models develop runoff and sediment yield from various agricultural land uses. One is a relatively simple continuous simulation-event type model that can be used to simulate long periods of record. The other is a more detailed event model that could be used for studying channel stability problems of individual events or short periods of record (1-2 years). Another recently developed event model, CREAMS (USDA, 1980) also appears to be quite useful because it simulates the effects of various conservation practices on sediment yield and runoff. The sediment transport-bed armoring model can route sediments by particle size distribution and density and can predict the development of an armor coat if the bed material is capable of developing one. Future improvements will enable the model to account for the non-uniform distribution of tractive force across the channel, especially in bendways, and to account for the erosion of bank slough material.

The following material will suggest how these models can be used in conjunction with the geomorphic concepts presented in Chapter 2 to identify processes responsible for instability and assess alternative corrective measures. We do not propose that these models are simple enough that anyone desiring to use them would be able to do so. We would expect that they would be available, along with personnel capable of using them, in district and division offices. The recent models developed by Simons and Li and used to study sediment transport in the Yazoo River Basin are similar to those described in this report. See specifically Li (1970), Chen (1979), and Simons and Li (1979).

6.2 PROCEDURES TO USE IN ASSESSING CHANNEL INSTABILITY

The following procedures are suggested for a complete assessment of (i) the processes responsible for instability and (ii) alternative corrective measures. In many cases evaluation to the extent described is not advisable and experience and engineering judgement should be used to select those most valuable to the project objectives. In almost all cases an experienced geologist or geomorphologist should be retained to study the

channel stratigraphy and make the geomorphic projections. He would also need to be available to work with the modeler in evaluation of output from the various hydrologic-sediment transport models. Hydraulic and soil mechanics engineers will be needed to perform the analyses of channel and bank stability.

Basic to any assessment of channel stability is a geomorphic evaluation that includes a study of the valley stratigraphy. Historic information should also be collected at this time. Subsequently, field surveys should be conducted. Data collected in the field should be based on the extent of the problem and the preliminary assessment. A log sheet should be prepared and used to record the following information for a variety of stream channels ranging in size from the main channel to "stable" channels in the upstream reaches of the drainage basin.

- Drainage area of basin and specific site
- Representative channel cross sections from which one can extract the top and bottom width, side slopes, maximum and minimum depth, and cross sectional area
- Valley and channel (thalweg) slope and channel sinuosity
- Valley width
- Watershed and flood plain land use, soils and geology maps
- Records of flood heights, discharges and sediment loads if available on the site and surrounding watersheds
- Stratigraphy and description of materials in each strata
- Locations of seeps or other conditions of bank weakness
- General description of the banks and bed noting specifically the location and characteristics of both stable and unstable sections and sediment depositional patterns
- Records of drill logs at selected cross sections of the valley

6.3 EXTENT OF PROBLEM AREA

Preliminary assessment of the watershed should indicate the extent of the problem. If bank instability is limited to a few points in bendways, at seepage sites, or places where debris or other obstructions have diverted the flow, this would be considered point instability. If the instability extends through more than one bendway but is stable immediately up and down stream for extended distances, this is considered as reach instability and could be attributed to the construction of a dam either up

or downstream, excessive sediment from a tributary source or unusual bank conditions that lead to extensive areas of weakness. However, if the channel system in its entirety appears to be deteriorating, then total channel system instability is likely the case. This extensive instability could be caused by climatic or land use change, loss of downstream control, and excedence of a threshold of stratigraphic structural stability. Each of these four cases must be treated in a different way and will be discussed in the following material. Geomorphic data such as described above is of particular interest in trying to evaluate total system instability.

6.4 AN EVALUATION OF THE TOTAL CHANNEL SYSTEM

In consideration of point, reach and total channel system instability, the latter is by far the most difficult to evaluate and solve. Therefore in the following presentation, total channel system instability is discussed first. We can then draw on this presentation in discussion of reach and point instability.

6.4.1 General Causes of System Instability

Total channel system instability can be caused by a variety of things either singly or in combination. These can be broken into four groups: (i) major land use change, (ii) climatic change, (iii) loss of downstream control and (iv) excedence of a threshold of stability in bank or bed material characteristics. The latter is usually associated with channel stratigraphy. The objective of the study is to determine which of the above, singularly or in combination, are responsible for the channel instability problems. It is much easier to treat the problem, if the source is known, than to treat the symptoms, as is frequently the case. It is also possible by determining the cause of the problem to carry out a preventive maintenance program and possibly keep similar problems from developing in adjacent stream channels. See Appendix E for a more complete discussion of these concepts.

6.4.1.1 Land Use and Climatic Change: Geomorphic evaluation carried out in conjunction with a study of historic information may give a clue to the causes of the problem. However as we shall show further on, reversal of a condition responsible for channel deterioration may not solve the problem. Historic information collected from some of the sourves previously listed can be used to indicate if major land use changes have taken place. By comparing dates of these changes, if there have been any, with dates and

descriptions of channel changes as taken from aerial photos or cross sections, it should be possible to determine if land use change is likely to have been a cause of channel instability. A similar type study of the rainfall records from the region should indicate if changing climate is likely to have been a cause of the problems.

6.4.1.2 Loss of Downstream Control: Loss of downstream controls and excedence of a threshold of stability are more difficult to evaluate. Changes in downstream controls can be associated with channel improvement, dredging and snagging or construction of dams. A dam constructed on a downstream channel can cause deposition in the channel under consideration. If the dam is constructed on a parallel tributary or the main channel above the confluence, it can cause changes in the levels and timing of flood peaks at the downstream confluence. In either case the structure can have a significant impact on the channel after construction. Channel construction activities are perhaps the most frequent cause of channel deterioration. Straightening of the channel for example, increases the slope and carrying capacity of the channel which may be all that is needed to exceed a threshold of stability. Tectonic activity in an area can also influence channel behavior; however, we do not address it in this presentation. Schumm (1977) has given a detailed discussion of the influence of tectonics on channel behavior.

6.4.1.3 Excedence of a Threshold of Stability: This category of causative factors requires a detailed evaluation of the channel stratigraphy and the physical characteristics of the various strata. At times threshold excedence can be very difficult to determine because the threshold that was exceeded may lead not to rapid spectacular failures such as may be expected if a lens of fine sand were exposed at the toe of the banks, but to slower and much less spectacular failures. For example, the exposed lens of material may be resistant enough to erode very slowly so that there would be a barely perceptible but progressive deterioration of the channels over a period of many years.

Channels that have deteriorated as a result of erosion or loss of strength of the materials that make up the bank usually have very irregular banks and scalloped sort of appearance. This is caused in part by variable resistance to erosion. It may also be caused by variable rate of headcut advancement (which in itself may be related to erosion resistance of the

material or climatic irregularities). Headcuts are frequently associated with both loss of downstream controls and failure caused by weakness of specific stratigraphic materials in the beds.

6.4.1.4 Failure Due to a Combination of Causes: Frequently channel deterioration is caused by a combination of the four categories with the last one, stratigraphic weakness of the banks, being the primary factor. It may have been triggered by either of the other three. That is, excedence of the threshold may have been due to a change in land use, climate, or loss of downstream control that conditioned the system to a point that rapid change could take place. Failure may also have been due to a single extreme flood event or an unusual combination of events, any one of which may not have exceeded the threshold. A study of the climatic history of the area could indicate which of these type problems are likely to have been the cause. It is also possible that excedence of a threshold of stability may go undetected for several years if the weakness is not extreme.

6.4.2 Episodic Erosion and Characteristic Channel Shape and Size

Total channel system failure is the dramatic period that Schumm (1977) refers to as the episodic erosion cycle responsible for the evolution of a drainage system. Figure 22 shows the gradual erosion of the valley floor over a very long period of time. Figure 22-a shows the erosion cycle following uplift as it is affected by isostatic adjustment to denudation, or rebound of the earth due to relief of overburden pressure as the surface is gradually eroded. Within the erosional cycle of the valley floor in Figure 22-a, episodes of erosion and dynamic equilibrium take place as shown in Figure 22-b. Figure 22-c shows in more detail the characteristics of the erosional cycles. At any given point in the channel system we observe periods of rapid erosion followed by a period of deposition and then a longer period of dynamic equilibrium. The pattern then repeats itself. Apparent, total channel system failure, is characteristic of the rapid erosional period. This will be followed by a period of deposition, and then by a longer period of dynamic equilibrium. The appearance of a stable channel prior to periods of failure is representative of the period of dynamic equilibrium.

During past times, these erosional periods moved progressively up through the watersheds as slow moving fronts. Just downstream from the

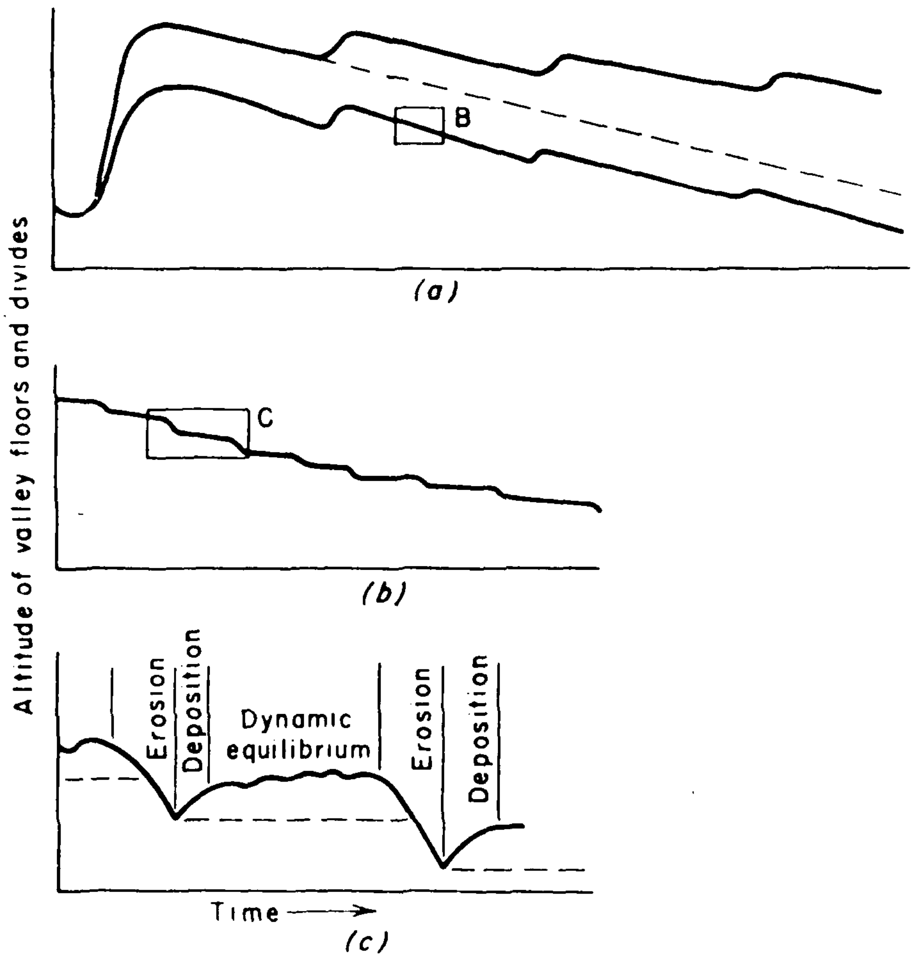


Figure 22 A concept of the erosion cycle after, (Schumm, 1977) (a) Erosion cycle following uplift as envisioned by Davis (dashed line) and as affected by isostatic adjustment to denudation, (b) Portion of valley floor in (a) above showing episodic nature of decrease of valley-floor altitude, (c) Portion of valley floor in (b) above showing periods of dynamic equilibrium, separated by episodes of instability.

moving erosional area was a region of transport, and below that area was a region of deposition. Observation of this evolutionary process at any point along the channel would give one a picture, over time, that looks like that in Figure 22-c.

The stream channels, during these different periods, had characteristic shapes depending upon the type of material through which they were flowing. For a channel in fine grained materials, the evolutionary pattern is shown in Figure 23. First, knickpoints develop and move progressively upstream (Fig. 23-b). Below the knickpoints the channels continue to widen as the banks fail due to undercutting or height instability (Fig. 23-c). They continue to get wider but somewhat shallower as debris from the failing banks starts to accumulate (Fig. 23-d). At this point the channels have become wide enough that the flows no longer carry away the debris and they begin to vegetate and eventually stabilize (Fig. 23-e). As the channel slopes become flatter, the carrying capacity begins to decline, fine materials start accumulating in the vegetation and the channel gradually becomes smaller, eventually returning to one somewhat like that shown in Figure 23-a. However, by this time migration of channel meanders has moved the channel back and forth across the valley. The net result is a slightly lower valley flood plain.

From the standpoint of use of the valley for agricultural purposes it would usually be desirable to keep the channel in the condition of dynamic equilibrium. But this is not always possible. Frequently, the channels are not deep enough to provide good drainage and overbank flooding can be a problem. However, characteristics of the channel, when in an equilibrium condition, can be used to estimate the causes of deterioration.

In Chapter 2 a variety of geomorphic relationships are presented. These can be very helpful in assessing the causes of the instability. Historical data such as old aerial photos, channel profiles and cross sections, records of drainage districts, etc. can be used to recreate the channel as it was prior to deterioration. Data from US Geological Survey stream gaging stations in the area can be used to estimate mean annual flow rates and peak runoff rates. With these channel and flow data, geomorphic evaluation of the reconstructed channel can be carried out. Values of the parameters relating the channel width, depth and velocity to the mean annual flow (Equations 8, 9, and 10) can be compared to those presented in

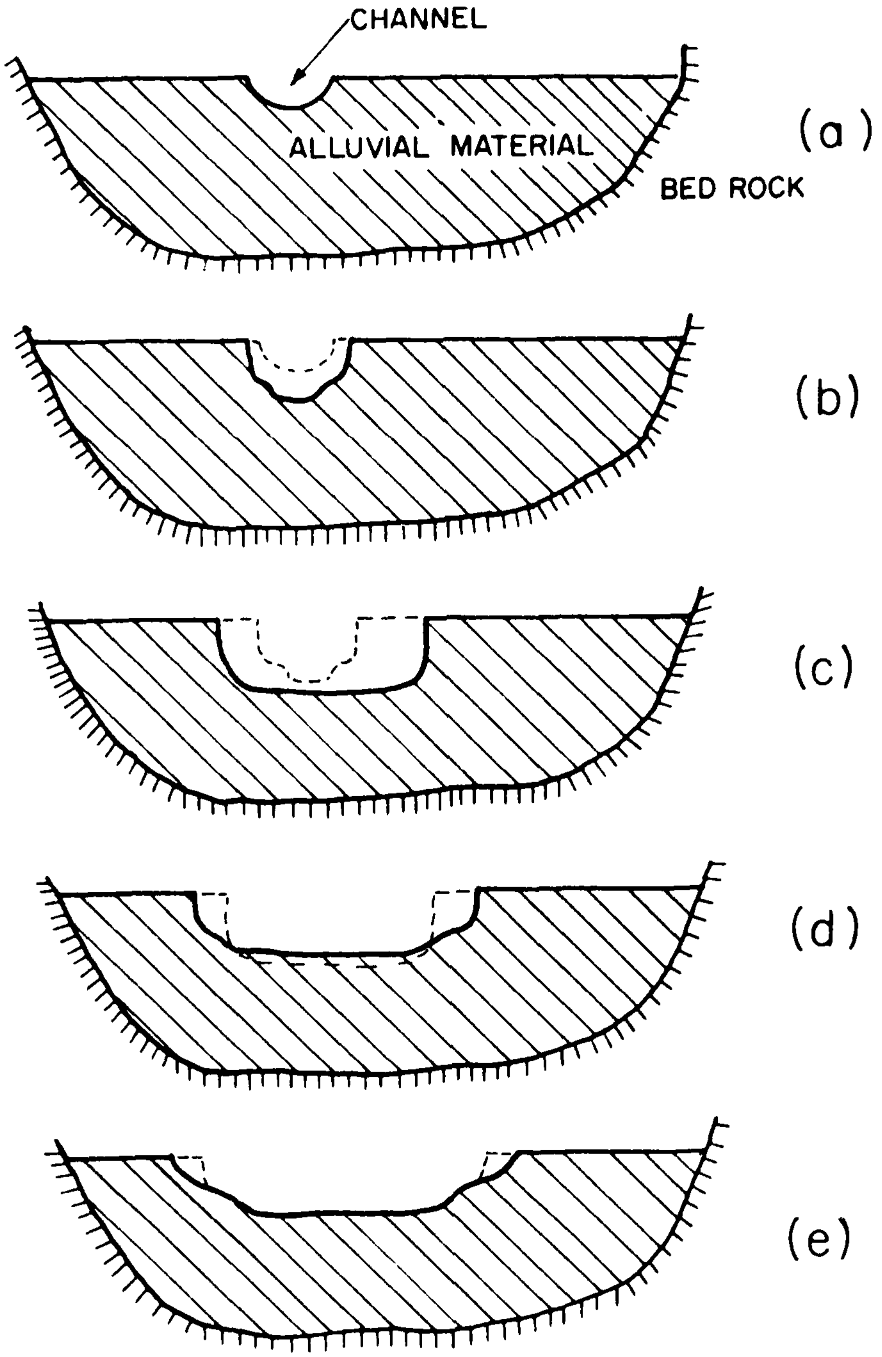


Figure 23 Evolutionary patterns in the degradation of a channel system
(a) stable channel prior to deterioration, (b) headcut,
(c) progressive deterioration and channel enlargement,
(d) channel continues to widen but becomes shallower, some material begins to accumulate at toe of the bank slopes,
(e) channels stop widening as vegetation begins to stabilize the material accumulating at the toe of the banks

Table 2 for both at-a-station values and collective values from all stations. A similarity of values would help support the validity of the reconstructed channel. The other geomorphic relationships that relate width, depth, width-depth ratio, sinuosity, and meander wave length to bank materials and flow rate can be used in the same way. After these expressions have been evaluated, and the best estimate of the old channel geometry has been developed, then the various geomorphic relations described in Chapter 2 including expressions 15, 19, and 20, which qualitatively relate the flow of water and sediment to channel characteristics,

$$Q_s d_{50} \sim Qs \tag{15}$$

$$Q \sim \frac{b,\ d,\ \lambda}{s} \tag{19}$$

$$Q_s \sim \frac{b,\ \lambda,\ s}{d,\ p} \tag{20}$$

can be used to estimate what the channel response should have been, given the changes in flow and sediment that may have occurred as a result of changes in land use, climate or downstream control. A comparison of that response with the observed channel should help to confirm the best estimate of the processes most likely to have created the present day channel instability problem.

It is now possible to supplement the geomorphic evaluation with output from hydrologic models. In Chapter 7 a relatively simple hydrologic model developed by Williams and Nicks (1980) has been coupled with a sediment routing model. It is a daily model that is simple enough that computer time required to simulate long periods of record is not excessive. Outputs from the model include mean daily flow and sediment by size fractions. The channel routing model accounts for aggradation and degradation by particle size, at various points along the channel profile. The hydrologic model can simulate a range of land uses and can, therefore, be used to help qualitatively assess impacts of change in land use and climate.

Historic information on land use, channel configuration and rainfall is usually adequate to enable one to simulate records prior to channel deterioration. Values of sediment transport are seldom available, but flow

records from the stream in question or adjacent streams may be used to assess the suitability of the model's performance. It is then possible to extend use of the model through the period of channel deterioration, by making adjustments for changing land use and rainfall and compare the model output with that from the watershed.

To determine if land use alone may have been responsible for part of the channel instability, the climatic pattern for the stable period of record can be repeated with the watershed land use changed to reflect recent trends. If the model indicates that some reaches are almost always free of deposited sediments when previous land uses would have shown some deposition, then these "clean" areas could be possible failure points if channel stratigraphic conditions are such that failure were possible. The model will also show the opposite if such were to be the case. For example, increased sediment loads from some areas may lead to sediment accumulation at points in the channel. Over bank flooding and a different type of channel instability would be indicated by this response.

In a similar manner it is possible to keep the land use constant as it was during the stable period, and to superimpose a new climatic regime equivalent to the recent period and determine if major changes are observed in the deposition or aggradation patterns of the channel.

Another hydrologic model is also discussed in Chapter 7 and in detail in Appendix I. It is a more detailed single event model that can be used to study the response of the channel to extreme events or unusual combinations of events. This model cannot be used in a quantitative sense, even though the model has quantitative capability, because there is usually not enough available information on the characteristics of the channel. However, since the model fairly accurately represents both overland and channel flow processes, general magnitudes of either channel aggradation or degradation would indicate whether or not these types of events were likely to lead to either loss of a downstream control or excedence of a threshold of channel stability.

Both of these models could also be used to study the response of the channel to activities such as construction of dams upstream or downstream and channel straightening or dredging. As in the previous discussion, results would have to be interpreted in a qualitative sense, to help support or counter conclusions obtained from geomorphic evaluation.

6.4.3 Consequences of an Enlarged Channel

The previous discussion of use of geomorphic and hydrologic models to study the factors responsible for channel deterioration were presented to help develop preventive techniques that can be used to keep similar types of instability from happening on adjacent watersheds. Material presented in Appendix E illustrate how regional stratigraphic information obtained in studying channel stability problems can be used to detect and identify weak points and probable failure, and to develop preventative measures to avoid the same problems on other streams.

In this section of the report we will address the problems of correcting or at least living with a channel system in a deteriorated state. In some cases it is possible to correct channel deterioration by correcting the situation that led to its deterioration. However, this is not generally the case. In this section of the report we will discuss some ways of working with channels for which the causative deterioration factors cannot be eliminated.

Channel deterioration, whether caused by a series of events such as land use change, climatic fluctuation, extreme events, an unusual sequence of events, or channel enlargement and clearing, usually results in a much larger channel. In some cases it is several times larger than the original channel, and can carry events within banks an order of magnitude larger than the events that the previous channel was capable of carrying. When this happens, overbank flooding becomes much less frequent. It is possible for a channel to get so big that overbank flooding can never occur. When overbank flooding no longer occurs or is very infrequent, much larger quantities of sediment are transported through the channel system, because there is little or no opportunity for deposition of the material on the flood plains. Flood peaks are also higher because there is no temporary out of bank storage to attenuate the peak rate and much larger rates of local surface runoff must cascade over the banks into the channel. Under normal circumstances velocities of local runoff would have been slowed by overbank flooding situations. As channel deterioration progresses up through the watershed, the expanding area in which the channel has become alienated from its flood plain causes the drainage density to increase, channel slopes to increase, and both flood peaks and sediment concentration also to increase. Since the transport capacity of the oversize channel is

so much greater, flooding and sediment deposition problems downstream also become larger.

In a channel system unaltered by man, this increased load of sediment downstream becomes so great that in the flatter reaches of the system, deposition begins. As the sediment loads increase, the much enlarged channels slowly fill with sediment and in these reaches out of bank flooding again begins to take place. As the channel erosion propagates up through the channel system, the deposition area also progresses upstream until, after some long period of time, the much enlarged channel is filled and all that remains is a terrace to indicate its existence. In the world we now live in, we depend so heavily on the alluvial soils of the country for food and fibre production and other uses, that we cannot allow the problems of deposition and flooding to occur, so we continue to dredge the channels and try to keep then open. Yet as long as the channels in the upper part of the system continue to degrade, sediment concentrations and flood peaks will increase. Until upstream channel erosion is stopped, the problems downstream will only grow in magnitude.

Associated with the type of channel instability described above is massive bank failure as described in Chapter 4. Depending upon the stratigraphy, various mechanisms are responsible for the failure. These can be weak spots caused by seepage, erosion of a weak lens of material, slumps and slides caused by high internal pore water pressure and combinations of these mechanisms. In almost all cases the driving force is the height and steepness of the bank. Under these circumstances, the banks will continue to recede until the debris from the banks accumulates and buttresses the bank preventing future failure.

All of these things combined indicate that several things must be considered in development of a channel stabilization program. Design flow rates and sediment concentrations must be based on those associated with a much incised channel with a very large drainage density. The stabilized channels must be made wide enough to pass the design floods without removal of the bank debris. The natural development of vegetation on the bank debris will of course increase its resistance to erosion, thus the sequence and magnitude of events that the channel experiences during its stabilization period may, to a large degree, determine the equilibrium dimensions of the channel; minor adjustments in width may then be observed.

6.6.4 Natural Channel Equilibrium Dimensions

There appear to be two major alternatives to solving channel stability problems. The least expensive, and in many cases the only viable alternative based on present technology is to let the channel seek its own equilibrium, but attempt to minimize total losses by watershed management. The techniques discussed in the next sections 6.5 and 6.6 on reach and point instability would then be used to keep the channel from further deterioration. In this case we must attempt to determine what size the channel is likely to become for a variety of land use treatments. There are several tools that we may rely on to estimate channel size. Perhaps the most reliable estimate (for existing land use) can be obtained from geomorphic measurements of the downstream reaches of deteriorated channels where stability may have been reached. Obviously the channels may vary tremendously in width and depth due to the wide range in degrees of resistance to erosion, but a survey of several channels in the region should give some indication of the ultimate width or width-depth ratios of the channels. Indications of approaching stability would be occurrence of few unvegetated banks, and the presence of vegetated debris along previously eroded banks. Channnel sinuosity and meander wave length are more difficult to estimate because of the dominant influence of the parent channel on the new channel location and the location and extent of areas of channel weakness.

It may also be possible to use some of the models previously described to aid in estimating channel dimensions. First, given the bank heights and slopes, the bank stability models can be used to determine how unstable the banks are. If they are marginally stable, then the rate of channel deterioration may be slow, with little change in the ultimate channel size. This type of bank stability may be controlled by some of the vegetative schemes discussed in Chapter 5 and Appendix C.

Hydrology models can also be used to help estimate channel size by assuming that the channels will stabilize themselves within a given number of years, say three, if no extreme events are experienced within this period of time. The problem then becomes one of finding a relationship between stable channel width and frequency of occurrence of the largest event that the channel can pass without experiencing velocities high enough

to remove the bank material or the slough from gravity failure of bank materials. Following are the steps necessary to develop such a relationship. This procedure will require use of a sediment routing model that can simulate lateral variability in tractive force (not yet incorporated into the model discussed in Chapter 7 and Appendix J.

(1) From flow records of channels representative of the channel under investigation, develop a flood frequency curve. If flow records are not available, the simple event model described in Chapter 7 can be used to simulate a period of record from rainfall records. It can then be used to develop a flood frequency curve.

(2) From the flood frequency curve, develop a cumulative probability distribution of events greater than a given amount.

(3) Estimate the most likely watershed land use and collect information needed to use the complex watershed model with sediment routing (model must include lateral variability in tractive force). Select a range of likely channel widths with typical bank debris deposits on each bank and then use the watershed topographic maps, channel profile, and watershed model to create, and route through the channel, a series of storm events of different magnitudes. Since the detailed sediment routing model modified to account for lateral variability will show the erosion of bank materials, study the response of the model over a fairly long reach of the channel; and for the width of channel selected, estimate which of the storm events could be tolerated without major bank erosion in straight reaches. Erosion on the outside of bendways should be expected.

(4) Select a new channel width and repeat Step (3) for the same series of storms and again estimate the tolerable storm.

(5) Repeat Steps (3) and (4) for several channel widths and plot a curve of channel width vs. tolerable peak rate.

(6) Compare these peaks with the cumulative probability curve developed in Step (2) and estimate a peak rate that, on the average, would not be exceeded in 2 or 3 years. From this it should be possible to estimate the channel width that would likely stabilize. The 2 - 3 year period, without an event, should be enough for vegetation to develop and protect the channel against larger events.

The above steps will provide an estimate that should be compared with observations as previously described. The models and estimates of their parameter values are not yet well enough determined to be able to use the output in other than a qualitative sense. However, the qualitative results should be good enough, along with observations of the channel in question and of similar channels, to guide one in selecting a likely stable size of channel.

After completing the above evaluation with the most likely watershed conditions for the past, it would be advisable to look at feasible alternative land use practices, to see if they have a significant impact on the stable channel widths. The same models would of course be used to estimate this impact. If the land use practices do have a significant impact, then the results could be used as a guide to selection of land use practices that lead to acceptable results. Even though such things as treatment of gullied areas and good land use conservation measures should be considered, the benefits of such measures may be difficult to assess, because lower sediment loads associated with such measures would enable the water to pick up large quantities of sediment from the channel. However, if the conservation practices also reduce the peak flow rates and volumes of runoff, this could offset to some extent the increased carrying capacity of clearer water. The only way to determine which is dominant is to test various alternatives using the model.

In studying these alternative land use practices and their impact on the naturally stabilized channel width, one must also consider the downstream impacts. It is hard to predict net downstream impact without looking at the total volumes and sizes of the sediments leaving the study reach. For example, a land use practice that leads to a relatively large sediment load may lead to a somewhat smaller stable channel, but the total sediment load, over a long period of time, to the downstream channel may be much greater than with better conservation practices. The better conservation practices might not reduce channel loads immediately, because the somewhat larger channels would contribute more sediment, but over a long period of time, after the channels stabilize, the new load could be much less. The vegetative impact of good conservation practices should also lead to a somewhat smaller median particle size distribution that would reduce downstream sedimentation problems.

6.4.5 Use of Structural Measures to Insure Channel Stability

If the land being protected is valuable enough, environmental impact and downstream depositional problems severe enough, or the potential damage that could be expected if the channel deterioration were allowed to continue severe enough, then it may be possible to justify structural measures in addition to land use practices to alleviate channel deterioration. The least expensive and possibly most effective structural means of improving the condition may be to place grade control structures in the channel. Chapter 5 and Appendix B describe the design of effective and inexpensive grade control structures in considerable detail. In most cases these structures can be used to remove up to 6 feet of fall, however the flow depth used in design of the structures designates a maximum allowable drop. This is discussed extensively in Appendix B.

Other structural measures such as training fences, dikes, armor, baffles, and combinations of riprap and vegetative protection may be needed at specific points above or between grade control structures. Although the scope of this report does not cover the selection or use of all these measures, sections 6.5 and 6.6 of this chapter discuss unstable reaches and points, and what to look for as indicators of future potential problems. Chapter 5 also describes other types of structural measures that should be considered. Another possibility that should not be taken too ligtly as a help in stabilizing banks is the importance of beavers. They may be responsible for stable bank conditions in many regions of the country.

6.4.5.1 Size and Location of Grade Control Structures: If the downstream reaches of a deteriorated channel appear to have stabilized and grade control is deemed necessary for upstream reaches, then, the most downstream structure should be located at the upper end of the stabilizing reach. However, if there is reason to believe that a new wave of channel rejuvenation (deterioration) is likely to develop, then it may be wise to place a grade control structure at the source of the problem or the furthest downstream point feasible.

In sizing a grade control structure, three criteria should be considered and the design based on the most limiting condition. These criteria are:

(1) Structural design maximum and minimum based on flow rates and channel width as defined in Chapters 5 and 6 and Appendix B.

(2) Establishing the grade at a level that will impart structural stability to the banks. This elevation can be determined by use of the bank stability equations described in Chapter 7 and Appendix D.

(3) If structural stability is caused by weak stratigraphic layers that were exposed at the base of the channel banks as the channel degraded, then the grade level should be raised enough to cover the exposed layers.

If structural design maximum or minimum preclude meeting the second and third criteria, then multiple low drop structures or higher vertical drop type grade control structures may be needed.

The use of a series of low drop grade control structures to control channel stability appears to have more potential than any of the other methods of channel protection, because it addresses more closely the source of the problem. However the proper size and spacing is difficult to determine. The actual hydraulic and structural design are not difficult, as described in Appendix B, once the amount of drop and width have been determined. The difficulty comes is selecting the amount of drop and spacing between structures. An optimum design would be one that leads to minimum net cost and would create a channel between structures that is in dynamic equilibrium. Low drop structures have a redeeming feature if properly designed. They are structurally efficient over a fairly wide range of physical drop. Therefore, the size of the structure should be based on the amount of fall that needs to be removed from the channel in order to bring stability to the channel banks.

The distance between grade control structures is much harder to estimate and depends upon the size, shape and slope of the deteriorated channel as compared to the original channel; the size of bed material; and conditions responsible for the deterioration, i.e., watershed change, loss of downstream control, etc. It is very important to remember that a deteriorated channel is completely out of equilibrium, therefore equations 19 and 20 cannot be used directely to estimate channel improvements likely to take place as a result of installation of the grade control structures.

For example, assume that channel deterioration came about as a result of loss of downstream control and stratigraphic weakness. Further assume that the deterioration has not progressed to the point of imparting massive changes in flow or sediment rates or channel sinuosity. Then in theory, if we were to place a grade control structure at the lower end of the reach in question and raise the bed to its original position, the channel slope would be reduced, deposition enhanced and the channel should gradually come back to its original size. However the time required for this to happen could be so long that the entire channel system upstream could deteriorate. In this case, the wise move would be to place at least two structures in the channel system, one at the upstream end of the problem area and the other at the lower end. The structure at the upper end should prevent further deterioration upstream and thus prevent massive changes in the regimes of both the water and sediment contributions. The number and location of intervening structures would depend upon the value of the land and rate of stabilization desired. Of course, all major tributaries entering the channel would need protection too. Given a long enough period of time, and assuming that the channel was not alienated from the flood plain, eventually the channel should return to its original size. The first adjustment after installation of the structure would be reduction in sediment loads as the material goes into storage in the channel bed. Reductions in numbers of bank failures would further reduce the coarse material load and the percent of total load made up of bed material. The finer sediment load would reduce the channel width as the fine material was deposited in the vegetation on the banks. If the structures were placed at the original channel grade elevation, and the channel fully recover; the deposition upstream from one structure would eventually extend to the structure above and there would be no break in slope.

In the previous example a change in downstream conditions was responsible for the deterioration. If land use or some change in the watershed upstream had been responsible, then equations 19 and 20 along with some of the other geomorphic relations could be used to estimate the stable channel shape that should eventually develop after grade control structures are in place.

6.4.5.2 Use of Analytical Models: In previous discussions geomorphic relations were used to estimate the channel conditions that might exist in

a stabilized system between structures. The analytical models previously discussed could also be used to help evaluate the channel response between low drop structures.

The simple hydrologic model and sediment routing scheme described in Section 7 can be used to simulate the channel response to projected grade elevations and the location of grade control structures. Since the model is quite efficient, it can also be used to study the response to alternative land use patterns. By assuming that grade control structures will prevent further widening by lessing gravity-induced failure, the aggradation pattern and thus the channel slope behind the grade control structures could be estimated by using the model in a continuous simulation mode and applying it to a representative 30 year period of record. The sensitivity of the response to various site locations, grade elevations and land uses could then be studied.

After selecting the best combination of grade and location, it would be advisable to study one of the reaches between structures in more detail. If the previous study were to show that a potential land use change could make a significant impact on the channel response, then a critical 2 or 3 year period of record should be selected from the record for closer evaluation. In this case, the more detailed watershed model, which should better evaluate land use response, combined with the sediment routing model, would be used to study the channel response. Initial channel bed elevations would be the same as they were in the previous study at the beginning of the selected 2 or 3 year period of record. An initial estimate of the armor conditions could be obtained by running the model for the events that occurred in a period of a few months prior to the selected period. In addition to looking at the channel bed, the potential for removal of bank failure debris as described in section 6.4.4 could also be investigated. This would tell whether or not continued bank widening is possible. If the channel instability has moved far enough into the headwaters to alienate the channel from its flood plain, then increased volumes of water may require a wider channel. The model should help detect this.

If the long period of record studied with the simpler model did not show a potential land use problem or solution, but did show a sensitivity to grade and location of drop structures, then a closer evaluation of a

critical 2 or 3 year period would be advisable. As in the previous case, the more complex watershed model and sediment transport model would be used. Comparison of the two models, over the same 2 - 3 year period would indicate whether additional studies are necessary.

In previous discussions, climate change is discussed as a possible cause of channel instability. If climatic change was responsible for channel deterioration, then it was probably in association with changes in land use that accompanied the climatic change. Since climatic change is something we have no control over, about all we can do is carry out analyses such as those discussed in the first of this section on evaluation of the total channel system. However, it is possible to use the detailed watershed model with the sediment routing scheme to observe the channel response to specific events such as an extreme storm system or a unique combination of storms. If evaluation of the channel system shows that such storm systems may have been responsible for channel instability, then it would be advisable to examine the performance of the grade control structures proposed for the channel with these same storms, but using the watershed and sediment transport models.

It must be remembered that the models discussed in the previous paragraphs have not been used extensively enough that output can be used quantitatively in design. However their use is recommended because experience in working with these models and the qualitative type information that they present can be valuable in future work.

In this section of the report, we have concentrated on methods to study total channel system instability and identify the processes responsible for deterioration. We have suggested that low drop grade control structures and watershed management are two of the best methods of control because they address the causes of much of the channel instability. They should be effective in controlling total channel system instability if costs warrant their use. However we must recognize that since the channels are dynamic, there will be areas such as bendways, seepage points, etc. where further bank erosion is likely. If the magnitude of this erosion is severe enough to require attention, then methods described in the next two sections of this chapter on reach and point stability should be considered.

6.5 AN EVALUATION OF REACH INSTABILITY

In the previous section of this chapter geomorphic and various bank stability and hydrology/sediment transport models were used to assess the causes of bank instability and evaluate the impact of alternative treatments. In this and the next section, many of these same procedures will be recommended in studying methods to protect unstable reaches and points.

Reach instability is caused by many of the same factors responsible for total system instability: land use or climatic change, loss of downstream control, and stratigraphic weakness. In many cases, what might normally be total system instability, may be limited to reach instability by such things as rock outcrops which provide a natural grade control. The construction of a dam can lead to reach instability immediately upstream and downstream of the structure or on adjacent tributaries. Natural or artificial channel cutoffs can also lead to reach instability. Variation in the characteristics of the channel banks and weak strata are frequently the cause of reach instability. There may also be reach instability between grade control structures that have been used to correct total system instability.

The field tours, geologic assessment, geomorphological evaluation, and model studies described at the beginning of this chapter should be used to assess the causes of reach instability. In general, reach instability can be found to manifest itself in problems of instability in the banks themselves or in energy related problems of sediment deposition, erosion, and transport.

6.5.1 Bank Stability Problems

If the reach instability is manifested in bank instability, then field studies and geological evaluation should point out the most likely cause or causes of bank failure. Possible problems are (i) banks too high to be structurally sound, (ii) banks that are too steep to stand without additional support, (iii) variation in physical characteristics of the material from point to point in the banks; for example, the intersection of the present channel with old paleo-channels or deposits of different age and thus different structural characteristics, (iv) weak stratigraphic layers or easily eroded materials in some strata, (v) basal scour, and (vi) high pore water pressure. The last two factors can be responsible for

failure by the other four methods. Appendix E discusses these types of problems extensively as they were evaluated in the bluff line streams of the Mississippi embayment.

After assessing the combinations of physical differences in the bank materials, the various bank stability models described in Chapter 7 and Appendix D can be used to determine their stability. They should also be used to determine the possible combinations of bank slope and height that would be stable. This information could then be used to select grade elevations for low drop channel grade control and to select various combinations of riprap and vegetative protection. Vegetative protection is particularly effective if the banks are only marginally unstable or can be made stable by a slope change that is compatible with vegetative procedures.

If the channel stability models show that removal of the slough material or bank failure debris is partially responsible for continued failure in the channels, then model studies should be used to help determine the equilibrium width between grade control structures; or in the natural channel, if grade control structures are not used. This might require several runs of the model to find the best combination of bank slope, channel width, and channel slope. If the channel appears to be much wider than desired, then consideration should be given to the use of riprap, training fences, baffles, dikes or vegetative measures to further control the channel erosion. These same structural measures should also be considered for protection of bendways.

6.5.2 Energy Dissipation and Sediment Transport Problems

If the unstable reach is upstream or downstream of a major structure, or on a parallel tributary of a stream with such a structure, then problems of instability may likely be caused by energy dissipation or sediment transport problems. However, the bank materials and their structural characteristics should be evaluated as described in the previous section. Energy related issues may have been responsible for initiating instability, but once a threshold of stability was exceeded, the physical condition of the banks may have then been responsible for a majority of the deterioration. If this is not the case, then the reasons for the instability should be investigated.

The most obvious cause of energy related-sediment transport instability problems is the location of a major structure in the vicinity of the unstable reach. If this is the case, then the channel behavior should be compared to that of a channel not affected by structures. The typical channel response to structures is described in section 4.2 of Chapter 4. A wide range of responses exist. The typical examples described in that section plus the examples found in Simons and Sentürk, 1976, can be used to determine the most likely cause of the instability. It would also be possible to use the hydrologic-sediment transport models, as described previously, to further assess the causes and investigate the impact that land use has on the stability. If high sediment loads are a problem, then gully stabilization and other changes in land use could be considered in attempts to reduce them. If excessive channel erosion caused by low sediment loads is a problem, then grade control structures to reduce the slope or various training devices could be considered. In all cases various vegetative and land use changes should be investigated because of their lower cost as compared to most structural measures.

If the unstable reach is associated with a channel instability that is likely to expand and lead to total channel system instability, attempts should be made to prevent further deterioration. Grade control structures at the location of a knickpoint, or on tributaries may be advisable. If natural controls are preventing further channel deterioration, then their long term stability should be investigated and enhanced, if necessary, by a permanent grade control structure.

If both bank instability and energy related transport problems are likely, then combinations of land use change, vegetation, bank shaping, grade control and other structural measures may be necessary. In this and all of the previous evaluations, the various geomorphic and hydrology-sediment transport models should be used to estimate the channel response to the various alternatives.

6.6 AN EVALUATION OF POINT INSTABILITY

All of the discussion of system and reach instability is equally applicable to individual points. However it should be easier to evaluate the cause of the problem and thus arrive at a solution. In addition to all of the appropriate material discussed in the previous sections, points of instability are frequently associated with excessive erosion caused by

isolated weakness in the banks or impingement of high velocities. Isolated weak points may be characterized by exposure of old paleochannels of weak materials, seeps and isolated pockets of easily eroded material. It may be possible to spot such points by study of soil maps, use of remote sensing and other techniques as described in Appendix E, and then to use preventive maintenance such as bank aggrading and combinations of vegetative and structural measures to prevent erosion before it starts. Use of such preventative measures may prevent areas of point instability from growing into major problems of reach and channel system instability. Correction of exposed point instability problems may be achieved by one of the previously discussed methods. The various models also previously discussed could aid in selection of the corrective measure.

It may be possible, in the future, to use the finite element model discussed both in Chapter 7 and Appendix K to study erosion associated with flow in bendways, at the base of dikes or training fences, or in the vicinity of drop structures. The examples used in determining use of the finite element model show how it can be used to define a changing erosion pattern or complex flow in channel intersections. With some additional work, they could be used to estimate the location and magnitude of scour associated with bendways or the ends of dikes, etc. This information would be useful estimating depths of protective measures or other instability criterion.

Land use change and its impact on point stability could be evaluated by using the complex watershed and transport models to estimate hydrographs of water and sediment at the point in question. By feeding the output from the hydrology-transport model into the finite element model, channel responses to different land use conditions could be obtained. It would also be possible to use the model to study alternative designs; i.e., effects of bank slope, radius of curvature, density of semipermeable fences, etc., as solutions to specific problems.

7 MATHEMATICAL MODELS

In the last few years mathematical models have been developed that can be valuable in assessing the causes of channel instability and studying the merits of various alternatives used to remedy the situation. A large number of these models, covering a wide range of applications in river and harbor hydraulics, are described in the 2nd and 3rd Annual Symposiums of the Waterways and Harbors and Coastal Engineering Division of ASCE (ASCE, 1975 and ASCE, 1976) and in :Modeling of Rivers: by Shen (1970). A recent publication (USDA Science and Education Administration, 1980) also describes a field scale model that is valuable for estimating the hydrologic response of a small watershed. Bank stability models in the literature are described by Thorne (1980).

Many of these models can be quite good in predicting the response of a watershed to specific changes. However, they must be calibrated to the specific watershed with a sizeable volume of data before any degree of reliability can be assumed. The CREAMS model and others described in this report require only minimal or no calibration data, but with these models it is not possible to quantitatively interpret the model output. However, if a model is a well developed, conceptually based, process oriented model, even if it is in error as far as actual prediction is concerned, may be quite useful in comparing alternatives, because the relative advantage of one system over another should be well indicated. Throughout this report, model use is suggested in this sense.

In the remaining pages of this chapter, various bank stability and hydrology-sediment transport models, recommended for use in the relative comparisons of alternatives, are described.

7.1 BANK STABILITY MODELS

The mechanisms of bank failure are described in Chapter 4. In this chapter, the equations used in calculating bank stability are given. Methods of obtaining the mechanical properties of the soils for use with these equations is described in Appendix D.

7.1.1 Noncohesive Banks

Since noncohesive banks cannot stand at an angle greater than the natural angle of repose of the material (the apparent angle of internal friction, ϕ), the factor of safety of a noncohesive well drained bank is the ratio of the tangent of the bank angle, θ, to the tangent of the angle of internal friction

$$F_s = \frac{\tan \theta}{\tan \phi} \tag{33}$$

The limiting condition is thus $\theta = \phi$.

If the bank is not fully drained, then pore water pressure may be significant and the limiting slope angle is (Thorne, 1980)

$$\tan \alpha = \frac{(\Upsilon Z_p \cos^2\theta - \mu) \tan \phi}{\Upsilon Z_p \cos^2\theta} \tag{34}$$

in which Υ is the bulk unit weight of bank material, μ is the internal pore water pressure, Z_p is the vertical depth to the failure plane, and α is the limiting slope angle. Equation 34 shows that if the internal pore pressure is significant α can be significantly less than ϕ. In many cases, where the channel banks experience rapidly changing water surface elevations, the natual bank angle in the region of fluctuation will be much less than the slope above and below it. This "bench" develops in the vicinity of the water surface because of the effect of pore water pressure on the natural bank slopes (See Figure 24).

If there are no pressure, tension, or fluid shear forces, the stability of a bank slope under submerged conditions is identical to that under drained conditions. However, most natural soil materials have a submerged angle of repose that is somewhat less than the drained angle of repose. Thus it becomes the limiting slope in submerged situations. Figure 24 shows the above terminology.

The retreat of noncohesive banks occurs almost entirely by erosion rather than by deep seated failure. Therefore, the above expressions must be used in conjunction with hydraulic expressions which take into account boundary shear stress and forces of lift and drag on the bank surface, especially in bends. See Thorne (1980) for more discussion of these impacts.

7.1.2 Cohesive Banks

The banks of stream channels in cohesive materials can stand at angles greater than the angle of repose (friction angle ϕ) of the material because of the effect of cohesion between particles of soil. Cohesive strength of the soil makes evaluation of bank stability more difficult. Retreat often takes place by structural deep seated failure. Figure 25 shows some of the

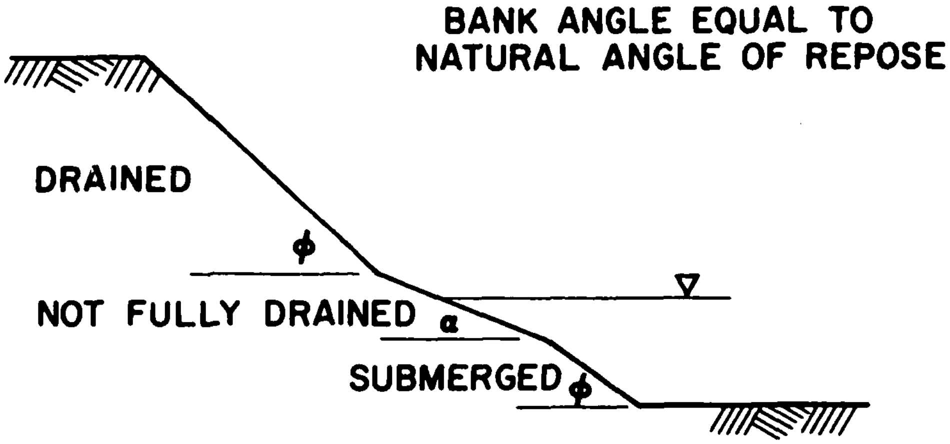


Figure 24 Noncohesive bank profile when subject to pore water pressure

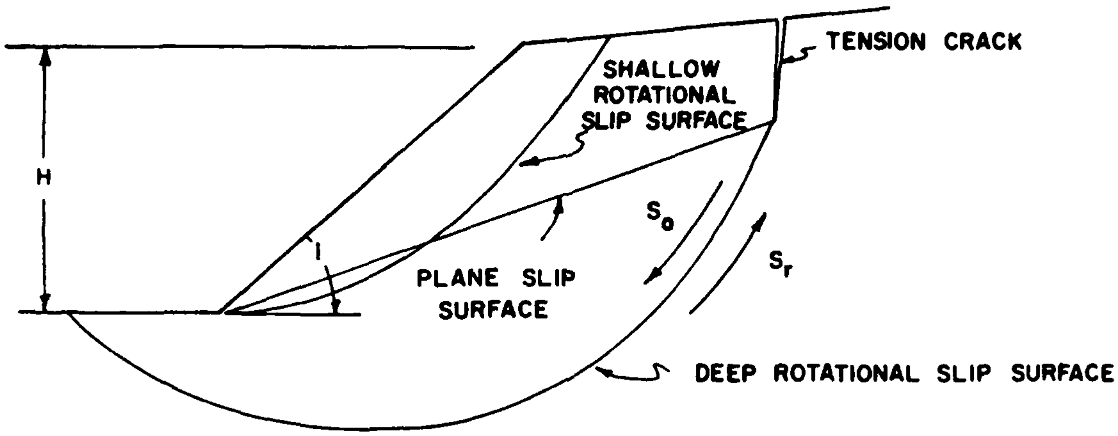


Figure 25 Cohesive bank failure surfaces

possible failure surfaces. Failure along any one of the surfaces occurs when the resistance to shear failure along the surface, S_r, is exceeded by the active force created by the weight of the bank material along the surface, S_a. The type of failure surface is a function of the cohesion, c; the friction angle, ϕ; the bulk weight of the bank material, Υ; the height of the bank, H; the bank slope, i; and the location and depth of tension cracks which are frequently found along banks in cohesive soils (Thorne, 1980 and Appendix D). The resistance to failure along a given surface is given by

$$S_r = c\ L + N \tan \phi \tag{35}$$

in which L is the length of the failure surface, N is the summation of the forces normal to the failure surface, and the other terms are as previously defined. The active forces tending to cause failure are given by

$$S_a = W \sin \theta \tag{36}$$

in which W is the weight of the bank material above the failure surface.

The most likely failure surface is obtained by assuming various failure surfaces and calculating the factor of safety, defined as the ratio of S_r to S_a. The most likely surface is the one with the lowest value of this ratio. Figure 25 shows several types of failure surface; these are deep rotational slip, shallow rotational slip, and plane slip. The likelihood of one or the other of the types of surface depends mostly on the bank height and slope. A plane slip that passes through the toe of the bank is most likely for very steep low banks. Deep rotational failures are most likely for high banks with low slope angles. Shallow rotational slips are more likely for intermediate heights and bank angles and on high banks in soils of low cohesion.

Calculated values of S_a and S_r for various bank heights and slopes may be used to find the most stable combination of height and slope for given field conditions. This information could help in arriving at the best alternative solution to bank stability problems as described in Chapter 6.

Deep rotational failures are usually analyzed by assuming a failure surface, either circular or log spiral (See Thorne, 1980), and dividing the soil body into a series of vertical slices. The total forces along the

failure surface are obtained by summing the forces on each slice. Figure 26 shows the forces summed in this method of solution. The factor of safety for a given surface is obtained by

$$F_s = \Sigma_B^A \, c\, b + (W - ub) \tan\phi \left(\frac{\sec\theta_F}{1 + \tan\theta_F \tan\phi}\right) \frac{1}{F_s \, W \sin\theta_F} \quad (36)$$

Symbols in Equation 36 and Figure 26 are as previously defined, and E_1 and E_2 are the normal forces between adjacent slices, X_1 and X_2 are the shear forces between adjacent slices, b is the thickness of the slice, θ_F is the angle of the failure plane to the horizontal, and u is the net pore water pressure. Solution is obtained by selecting centers of rotation and calculating F_s for each. By plotting the values of F_s at the center of the rotational failure surface, it is possible to map the values of F_s and thus locate the most critical solution.

Shallow rotational slips may be analyzed as a planar slip if the depth of rotation is not extreme. A comparison of the factors of safety, or stability numbers, obtained by the following method compared to solution by the method of slices presented above will indicate the amount of error. If the error is not excessive, the Culmann Method (Thorne, 1980 and Appendix D) is the easiest to use if tension cracks are not present and positive pore water pressures can be ignored.

The failure surface for solution by the Culmann method is shown in Figure 27. The critical height, H_c, for a bank of a given slope is given by (Thorne, 1980):

$$H_c = \frac{4c}{\gamma} \frac{\sin\theta \cos\phi}{(1 - \cos(\theta - \phi))} \quad (37)$$

in which the symbols are as previously defined. A dimensionless measure of the stability, the stability number, which is the ratio of forces F_1 and F_2 (see Figure 27) can be shown to be (Taylor, 1948):

$$N_s = \frac{c}{\gamma H_c} = \frac{1 - \cos(\theta - \phi)}{4 \sin\theta \cos\phi} \quad (38)$$

In soils subject to tensile cracking, the location and depth of the crack must be considered in estimating critical bank height. Thorne (1980)

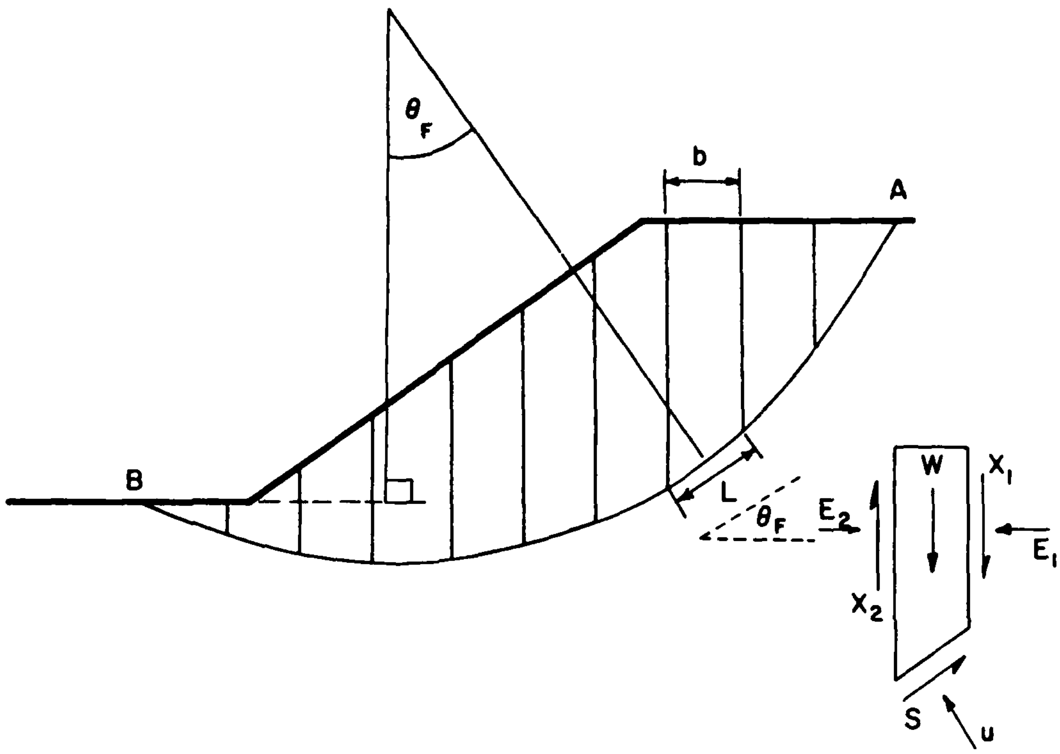


Figure 26 Deep rotational failure surface (After Thorne, 1980)

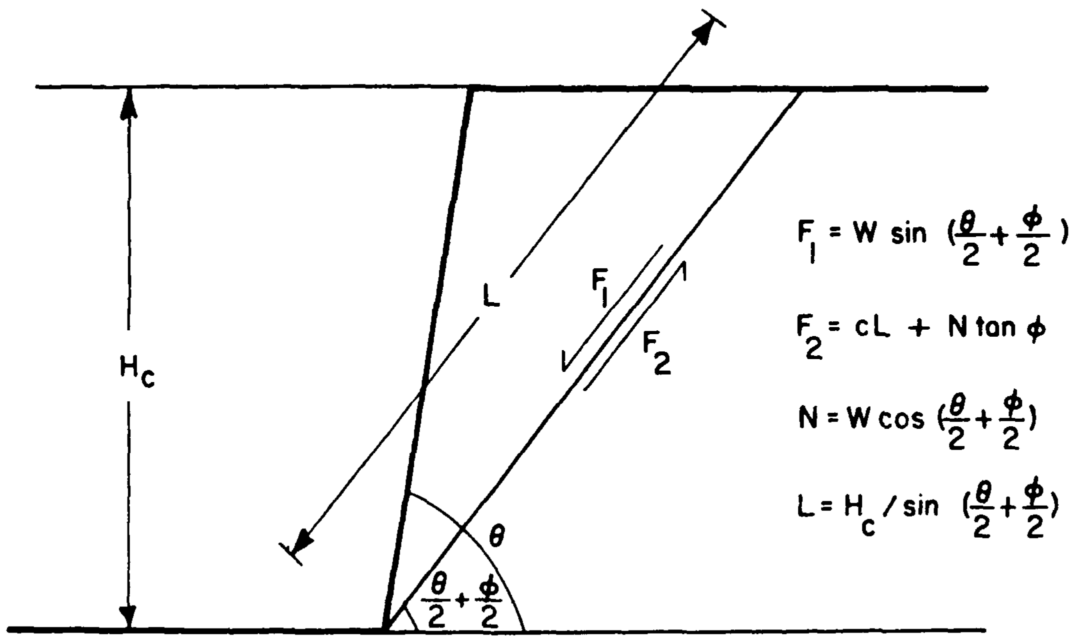


Figure 27 Planer failure through the toe (After Thorne, 1980)

shows that the critical height H_c' for a vertical bank in soils of low tensile strength is given by (see Figure 28):

$$H_c' = \frac{2\,c}{\gamma} \tan\,(45 + \frac{\phi}{2}) \tag{39}$$

and $H_c' = H_c/2$.

However if the tensile strength is appreciable, as it can be in some soils, then the depth of cracking may be less than the depth of tensile stress, Z. In this case the depth of cracking, Z, is defined as

$$Z = Z_o\ (1 - \frac{\sigma_{tc}}{\sigma_t}) \tag{40}$$

in which σ_{tc} is the tensile strength, and σ_t is the tensile stress at the surface. The width, b, of the failing slab can also be calculated (Lohner and Handy, 1968). It is given by

$$b = \frac{H_c - y}{\tan\,(45 + \frac{\phi}{2}) - \tan\, i} \tag{41}$$

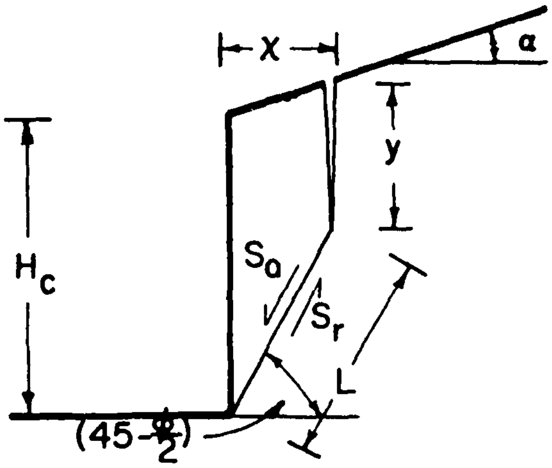
For a more complete discussion of these expressions and limitations of their use, see Thorne (1980) and Appendix D. Thorne also presents a stability chart that can be used for the solution of log spiral toe failures of banks with tension cracks.

7.1.3 Composite Banks

Failure surfaces in composite banks are a function of the strata that make up the bank and the engineering properties of the strata. There are many combinations of stratification that are possible, but they can be classified into two general categories (i) that where a noncohesive layer overlies a cohesive one and (ii) that where a cohesive layer overlies a noncohesive one.

The presence of cohesive material below gravel or noncohesive material is the most stable and usually results in the formation of a bench that protects the noncohesive material from fluvial erosion and over-steepening except at high flows.

The presence of noncohesive material below a cohesive layer leads to fluvial erosion of the noncohesive material and thus oversteepening of the



$$S_a = W \sin\left(45 - \frac{\phi}{2}\right)$$

$$W = \chi \gamma \left(\frac{H + y}{2}\right)$$

$$S_r = cL + N \tan\phi$$

$$N = W \cos\left(45 + \frac{\phi}{2}\right)$$

For the critical case $S_a = S_r$ and:

$$H_c = \frac{4c}{\gamma\left[\cos\phi - 2\cos^2(45+\phi)\tan\phi\right]} - y$$

$$= \frac{4c}{\gamma} \tan\left(45 + \frac{\phi}{2}\right) - y$$

Figure 28 Failure of a vertical bank with tensile crack

bank. Thorne (1980) describes three typical failure mechanisms of this condition, deep rotational slip, plane slip and cantilever failure. Erosion of the noncohesive layer results in oversteepening of the bank and if the bank is high, deep rotational slip is likely to occur with the critical failure surface above, or tangential, to the contact with the noncohesive layer. The location of the noncohesive layer dictates whether the failure is at, above or below the bank. Thorne (1980) suggests that analyses developed by Morgenstern and Price (1965) and Sarma (1979) may be improvements over conventional methods when dealing with composite banks because their approach does not require any assumed failure surface geometry.

If the cohesive layer, above the noncohesive one, is relatively thin or the banks are low, then plane slips are likely and the Culmann analyses described previously may be used to determine stability.

If the cohesive layer is fairly strong and is able to stand as a vertical cut (loessial soils), then erosion of the underlying noncohesive material will generate an overhang or cantilever. Failure of these surfaces is by shear, beam, or tensile force depending upon the strength of the material and geometry. Thorne (1980) and Thorne and Tovey (1981) present a series of stability charts for cantilevered banks that may be used to estimate the mechanism of failure and factor of safety. Tension cracks and fissures are very likely in this type bank and to a great extent determine the failure surface.

7.2 HYDROLOGY - SEDIMENT TRANSPORT MODELS

Alluvial streams are dynamic systems that continuously change their configuration and state in response to either changes in the natural environment, or perturbations introduced by man's activity. Among the leading causes are several that are intimately associated with land-management and conservation practices carried out on the upland areas. The combined effect is an aggregate flow of water and sediment coming from a variety of point and non-point sources within the upstream watersheds. This aggregate yield acts as a time and space dependent loading on streams draining the watersheds. If this loading becomes quite different from that which the streams have adjusted to, the result is a breakdown in the stability of the channel system. The watersheds contributing to the loading of any given channel exhibit, in general, a great variety of soils,

vegetation, and land uses. In order to effectively assess the impact of these watersheds on the loading of the channel system and given the economic and time limitations of field studies, it was necessary to develop alternative methods for predicting the stream loadings. A viable alternative was found in the development of mathematical models through which the hydrology of a watershed can be simulated and the effects of various management practices understood and predicted.

Two different watershed models have been considered: a single event model and a continuous simulation model. The bulk of sediment usually moves during the occurrence of a few events in a given season. Therefore, a single event model was developed to simulate the short-term movement of sediment. This is a physically-based model, and is briefly described below. The details of this model are presented in the Appendix I. For long-term simulation of sediment movement the daily yield model developed by Williams and Nicks (1980) has been implemented. This is basically a physically-based lumped model used to predict the water and sediment coming out of the sub-watersheds, and is used in conjunction with the single-event channel component. The structure of the model is presented below. Additional details can be found in the paper of Williams and Nicks.

7.2.1 Single-Event Watershed Model

The model consists of two intertwined models: one describing the hydrology of the basin; the other describing the associated erosion and sedimentation processes. It simulates the movement of water and sediment as a time and space distributed process, and has the ability of distinguishing between overland and channel flows. The watershed is regarded as consisting of a mosaic of individual but interconnected subcatchments. Within each of these subcatchments, the characteristics of the terrain and precipitation distribution are assumed uniform. The model can thus be regarded as a cascading process in which the output of one or more subcatchments becomes the input to another subcatchment or channel reach. In reproducing the overland movement of water and sediment, the model simulates processes of interception, infiltration, runoff, sediment detachment, sediment transport, and sediment deposition. The water and sediment reaching the streams are routed through the channel system; rates of channel aggradation and degradation are computed. These components are outlined in the following sections.

7.2.1.1 Interception: Interception is treated by computing the amount of rainfall retained on vegetative cover, plus an amount lost by evaporation during a storm event. Surface depression storage is combined with interception and considered as an initial loss.

7.2.1.2 Infiltration: This component simulates the process of infiltration using a two-parameter model developed by Smith and Parlange (1978). It is applicable to rainfall on ponded conditions on a homogeneous soil. By assuming that hydraulic conductivity varies slowly near saturation, an approximate solution is obtained by describing the process as diffusion of water under gravity forces. The solution predicts ponding time and infiltration rate decay for arbitrary rainfall rates. It uses two parameters: saturated soil conductivity, and a parameter that is related to the soil sorptivity.

7.2.1.3 Overland and Channel Water Routing: Rainfall excess is routed to the nearest channel system using a procedure based on the kinematic-wave approximation of the flow equations. The scheme is computationally efficient, and preserves the effects of kinematic shocks without the usual complications (Borah, et al., 1980). The output includes flow depth and discharge as functions of time and space.

7.2.1.4 Overland Sediment Routing: This component computes the splash erosion rates and the amount of soil eroded and transported by runoff. The rate of soil detached by raindrop splash is related to the second power of rainfall intensity, soil erodibility, and cover conditions. Soil erodibility is a user supplied parameter, usually adjusted by calibrating the model. However, data presented in Appendix G provides sufficient information for a prior estimation of the soil erodibility for a number of soils and cropping conditions. Detachment (or deposition) by runoff is a function of transport-capacity excess (or defect) over available loose soil. Transport capacity is estimated using one of several transport formulas incorporated into the model. Criteria for selection of the transport law is discussed in detail by Alonso et al. (1980). Detached sediment is routed by size fractions using a scheme based on the continuity equation for sediment. The fractions used in the simulation are supplied by the user. Appendix G gives some guidelines regarding the size distributions that may be expected from certain soils.

7.2.1.5 Channel Sediment Routing: Two parallel schemes are used to route sediment down the channel system. A simple scheme is used to simulate the movement of sediment loads composed of relatively fine particles. Bed scour is represented as a function of transport capacity excess over available loose soil, while deposition is a function of excess load over transport capacity. The eroded material is routed using a characteristic solution of the sediment continuity equation. This solution assumes the sediment load moves with the same celerity as that of the water waves and, for this reason, the component is restricted to relatively fine material. Within this restriction, the model can route different size fractions.

A more elaborate scheme is used to model the instream transport of well graded sediment mixtures, and the evolution of bed processes. This is done by introducing algorithms that account for effects such as total-load lag, residual transport capacity, and availability of bed material. The scheme permits simulation of bed armoring, and can be run either as a coupled-unsteady model to predict transient movement of water and sediment, or as an uncoupled, known-discharge model when only bed processes are of interest. This scheme is described in detail in the Appendix J.

7.2.2 Input Data

Input data required for the single-event simulation model includes: rainfall intensity, aerial distribution of rainfall, and mean evaporation rate, initial interception storage, saturated hydraulic conductivity, sorptivity, antecedent soil moisture content, initial loose soil storage, canopy and low ground cover density, average height of low ground cover, ratio of high ground cover density to total ground cover density in channels, ratio of the interception storage capacity of a typical canopy cover to that of the ground cover, ratio of evaporating surface to the horizontal projected area of ground cover, area and slope of overland segments, slope length of overland and channel segments, bed slope of channel segments, wetted perimeter versus flow area relationships, water temperature, a parameter describing flow resistance, representative size of sediment fractions, specific gravity of sediment size fractions, percentage of size fractions in the soil sample, a parameter identifying soil erodibility by rainfall, a parameter describing surface runoff erosion, and maximum penetration depth of raindrop impact.

7.2.3 Continuous-Simulation Watershed Model

In this model the watershed is segmented into a series of homogeneous subcatchments interconnected by a channel network. Water and sediment are routed down the channels using the simple channel component described above. The daily water and sediment yields from each of the subcatchments are estimated using the SWRRB (Simulator of Water Resources in Rural Basins) continuous simulation model presented by Williams and Nicks (1980). A brief account of its components is given below.

The model is essentially a modified version of the CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (USDA, SEA, 1980) model. Modifications enable the model to be applied to large complex, rural basins. The major processes included in the model are surface runoff, percolation, return flow (sub-surface flow), evapotranspiration, reservoir storage and sedimentation. The hydrology model is based on the water balance equation

$$SM_t = SM + P - Q - ET - O - QR \tag{42}$$

where, SM is the soil moisture content at the beginning; SM_t is the soil moisture t days later; P is the amount of rainfall; Q is the amount of surface runoff, ET is the amount of evapotranspiration; O is the amount of percolation below the root zone that does not appear as return flow in the basin, and QR is the amount of return flow during a t day period.

7.2.3.1 Surface Runoff Volume: Surface runoff is predicted for daily rainfall using the SCS curve number technique (USDA, SCS, 1972). Traditionally, the SCS has used an antecedent rainfall index to estimate three antecedent soil moisture conditions (I-dry, II-normal, III-wet). In reality, soil moisture varies continuously and thus the curve number has many values instead of only three. This deficiency was overcome by linking the curve number technique with evapotransporation and percolation models. Input to the models are daily rainfall, soil moisture content in the root zone, upper limit of soil water storage in the root zone and the Number II moisture condition and the curve number (available from USDA, SCS, 1972) for most soil types. The technique gives a good estimate of the retention parameter, and thus the runoff, if soil water is distributed uniformly in the soil profile. A weighting technique is used to account for the soil water distribution. The root zone is divided into several layers and weighting factors (decreasing with depth) are applied. Estimates of the peak runoff rate are based on the Rational Formula and time to peak.

7.2.3.2 Percolation: The percolation component uses a storage routing technique combined with a crack-flow model to predict flow through the root zone. Water is routed through each of the seven soil layers in the root zone and through an eighth layer below the root zone. Once water percolates below the eighth layer it is lost from the basin (becomes groundwater or appears as return flow in downstream basins). Water stored in the eighth layer cannot be used by plants, but can become return flow. Percolation does not occur when the water content is below field capacity. The crack-flow model allows percolation of infiltrated rainfall even though the soil water content is less than field capacity. When the soil is dry and cracked, infiltrated rainfall can flow through the cracks of a layer without becoming part of the overlying, layers of soil water. However, the portion that does become part of a layer, cannot percolate below the layer until storage in the layer exceeds field capacity. Inputs to this component are the amount of water stored and field capacity of the soil layers, and estimation of travel times through the layers.

7.2.3.3 Return Flow: The eighth soil layer is added to the model to simulate return flow (subsurface flow). Water that percolates below the root zone into the eighth layer is divided between percolation to groundwater and return flow. The hydraulic properties of the soil in the eighth layer and those of the soil below the eighth layer dictate the allocation of water to groundwater and return flow. Return flow is simulated with the same storage routing techniques used for percolation. Inputs to this component are the amount of water stored and field capacity of the eighth soil layer and an estimate of the return flow travel time (time required for subsurface flow to move from the centroid of the sub-watershed to the subwatershed outlet) in days. The predicted daily return flow for each subwatershed is composited and added to the composited surface runoff as an estimate of daily water yield.

7.2.3.4 Evapotranspiration: The evapotranspiration (ET) component is the ET Model developed by Ritchie (1972). Potential evaporation is computed from daily temperature, daily solar radiation, solar radiation albedo and a psychrometric constant. The model computes soil and plant evapotranspiration separately. The soil evaporation is based on potential evaporation and leaf area. Leaf area index is defined as the area of plant leaves relative to the soil surface area. Plant evaporation is estimated

from potential evaporation, leaf area index, soil moisture and field capacity. Once total ET is computed for a particular day, its loss is distributed to the soil layers.

7.2.3.5 Water Balance for Reservoirs: The water balance for reservoirs component is designed to account for the effects of farm ponds on water yield. The water balance equation is

$$VM = VM_o + QI - QO - EV - SP \tag{43}$$

where VM_o is the volume of water stored in all reservoirs within a sub-watershed at the beginning of the day, VM is the volume at the end of the day, QI is the inflow during the day, QO is the outflow, EV is the evaporation, SP is the seepage. The inflow, QI, is composed of surface runoff from the total reservoir drainage area and rainfall on the water surface area. Outflow occurs when the volume exceeds the permanent pool storage capacity. The evaporation is computed based on the potential evaporation and the surface area of all reservoirs in the sub-watershed. Seepage from the reservoir is computed from the saturated conductivity of the reservoir bed and the surface area.

7.2.3.6 Sediment Yield: Sediment yield is computed with the Modified Universal Soil Loss Equation (MUSLE) (Williams et al., 1977). Inputs to the equation are the composited surface runoff volume for the sub-watershed, peak flow rate for the sub-watershed, soil erodibility factor, crop management factor, the erosion control practice factor and the slope length and steepness factor.

7.2.3.7 Summary of Input Data: Following is a summary of input data required for use of the continuous simulation model (Williams and Nicks, 1980):

(1) Computation Duration: Number of years of runoff simulation.
(2) Crop Management: Number of crops grown during each simulation year (two crops per year, e.g., cotton and corn, etc.), leaf area index for each crop.
(3) Geometry Data: Sub-watershed area in square miles.
(4) Weather Information: Daily rainfall, monthly rainfall intensity factors, Fourier Coefficients for daily temperature in degrees Fahrenheit, Fourier Coefficients for daily solar radiation.
(5) Water Routing Parameters: Number II condition (normal) SCS curve number (CN) from National Engineering Handbook (USDA, SCS, 1972),

a Coefficient in the rainfall intensity amount relationship that is the ratio of the amount of rainfall that occurs prior to the time of concentration, to the amount that occurs in 24 hours, coefficient of variation for peak flow.

(6) Soil Erosion (MUSLE) Parameters: Soil erodibility factor (K), erosion control practice factors (P), slope length and steepness factors (LS), monthly crop management factor (C), and runoff factors from (5).

(7) Soil and Sub-surface Information: The soil in the sub-watershed is divided vertically into 8 layers. The top layer is 1/36 of the root depth, the second is 5/36, and the lower ones are 1/6 each. Inputs are: root depth in inches, total porosity, soil water content at 15 Bars moisture content, soil water content at 0.3 Bars moisture content, saturated hydraulic conductivity, and return flow travel time.

7.2.4 Two-Dimensional Models for Evaluation of Sediment Movement at Specific Sites

In many instances there is a need for predicting water and sediment movement in specific channel reaches in which flow properties in longitudinal and transverse directions are variable. In such instances simple one-dimensional models do not suffice because they only give information on longitudinal flow variations. It is then necessary to resort to higher-dimensional models.

Flow problems that consider the complete region of interest are generally three-dimensional and the governing flow equations are elliptic in nature (constant or piece-wise continuous water discharge is assumed). Numerical solution of three-dimensional elliptic equations is computationally, very expensive and only rather coarse computational grids can be used with most computers. This leads to poor resolution of the flow field. Use of three-dimensional models is therefore not attractive at the present time.

Fortunately, in many stream reaches, certain flow scales dominate over others so that the equations can be simplified accordingly. For instance, when flow variations over the depth can be neglected, as compared to lateral changes, the problem can be reduced to solving a quasi-horizontal flow, by depth-averaging the three-dimensional flow equations. Similarly,

if lateral flow variations are not significant, the solution domain is simplified to a two-dimensional vertical region, by width-averaging the three-dimensional equations, or by assuming an infinitely wide flow. In both cases the flow equations are reduced to a manageable set of two-dimensional elliptic equations. The sediment movement is represented by a set of two-dimensional unsteady equations which can be hyperbolic and/or parabolic in nature, depending on how the sediment load is characterized. This approach permits simulation of local changes in stage and bed elevations without requiring work in the three-dimensional domain.

Two codes have been written based on two-dimensional finite element schemes. Their formulation is described in detail in Appendix K. These schemes were used to simulate several specific flow situations. One of them, back-filling of a trench is presented in Chapter 8 of this Report. The others are included in Appendix K.

7.2.4.1 Input Data: For any two-dimensional model of the type discussed in this Report, the input data required can be subdivided into three main classifications. First, the data required to define the geometry of the channel reach and any flow control structure in it, must be furnished. Second, information regarding the properties of the flow constituents must be presecribed. Namely, water temperature, sediment size distributions, density of sediment fractions, etc. The final category concerns the incoming flow of water and sediment load to which the channel reach is subjected. In view of the wide variety of boundary and flow conditions which may be encountered in practice, the subject of input data for specific simulations will not be dealt with here. Instead, examples of input data requirements are given in Appendix K.

8 GOODWIN AND JOHNSON CREEK WATERSHEDS IN PANOLA COUNTY, MS

This chapter is a description of Goodwin and Johnson Creek Watersheds in Panola County, Mississippi. It is in these two small watersheds that much of the research concerning channel stability was conducted. Geomorphological investigations and observations of grade control structures and channel revetment were made on many other bluffline tributaries. Results of these investigations are reported in Appendices A and E. Descriptions of Goodwin and Johnson Creeks include the watershed characteristics, channel stability problems, grade control and other installed devices, watershed data collection facilities, and applications of selected watershed models.

8.1 WATERSHED CHARACTERISTICS

The following section of the report on watershed characteristics describe the location, climate, soils, land use, geology and geomorphology of Goodwin and Johnson Creek Watersheds. Most work is centered in the Goodwin Creek Watershed; therefore, the above descriptions are complete for this watershed. Only selected data are available for the Johnson Creek Watershed.

8.1.1 Location

The location of Goodwin and Johnson Creek Watersheds is in the bluff line east of the Mississippi Delta in the Yazoo River Basin. This bluff line is a belt of deep loess soils bordering the east side of the Mississippi River alluvial plain, extending from Memphis, Tennessee to Vicksburg, Mississppi. In Panola County, the location of the study, the belt ranges in width from 10 to 26 miles and the loess soils range from 4 to 50 feet in thickness. The bluff line tributaries have many channel stability problems similar to those in other areas of the United States. Tributaries contribute large quantities of sediment to the Yazoo River; this is a problem for downstream navigation. Even though cultivated fields in the watersheds contribute large quantities of sediment, the channel itself also contributes greatly. Figure 29 shows the location of the watersheds in Northern Mississippi.

8.1.2 Climate and Climatic History

This region of the country is humid and hot in summer and mild in winter. A nearby national weather service station (Batesville 2SW) has normal annual precipitation of 53.52 inches. Table 3 shows the monthly

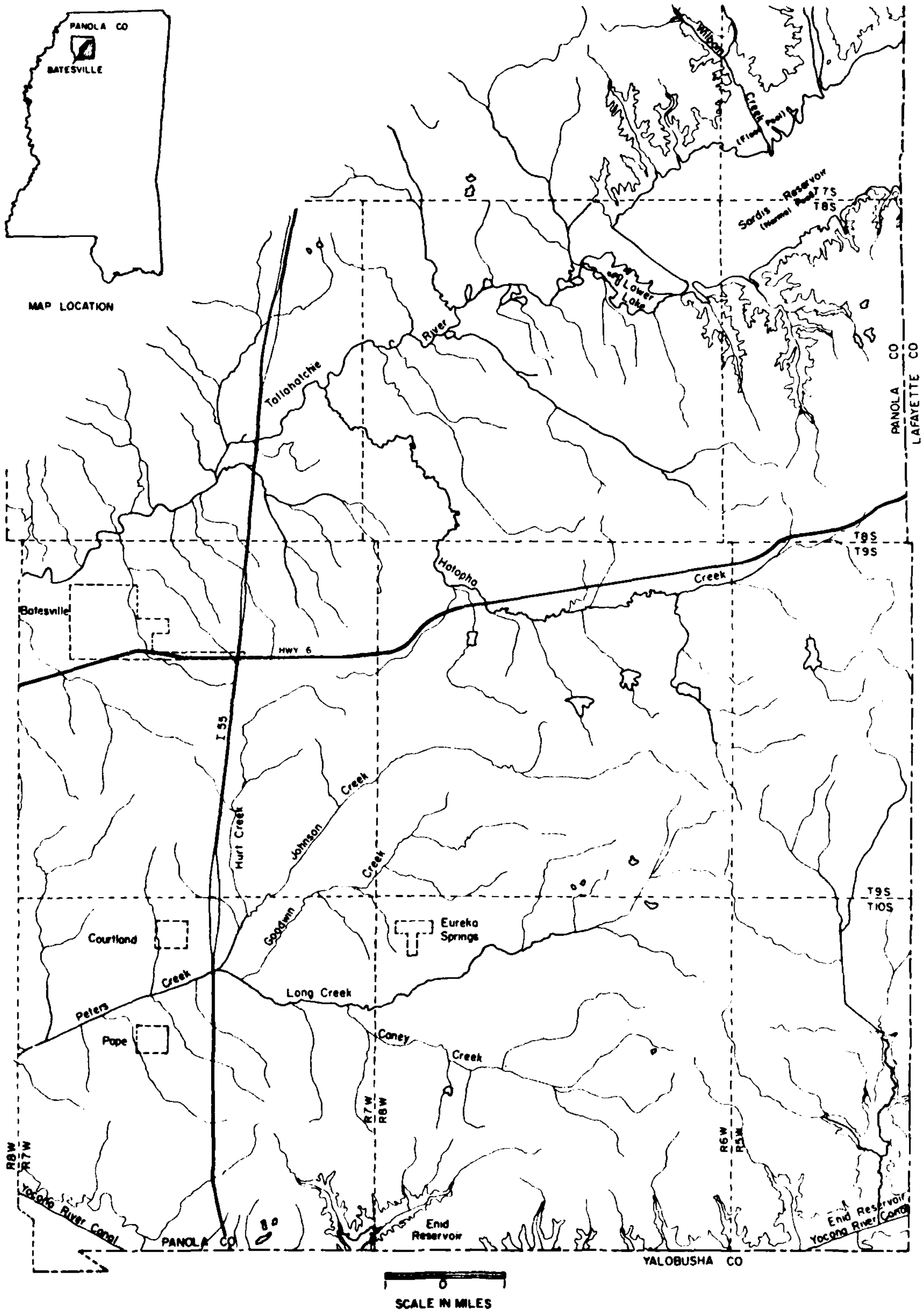


Figure 29 Location Map, Northwest Mississippi

Table 3 Normal Temperature and Precipitation - Goodwin Creek
Source: National Weather Service Station Batesville 2SW
for Period 1941-1970

	Normal Temperature (°F)	Normal Precipitation (Inches)
January	42.0	5.12
February	45.2	5.19
March	52.0	6.12
April	63.2	5.93
May	70.7	4.30
June	77.9	3.31
July	80.7	3.99
August	79.7	3.26
September	73.5	3.57
October	62.8	2.63
November	51.8	4.69
December	44.1	5.41
Annual	62.0	53.52

distribution of average daily temperature and precipitation. In this area most precipitation occurs in winter and spring; primarily in the form of rainfall, with very little snow or sleet. The winter-spring rainfall generally comes from warm moist air from the Gulf of Mexico. The summer-fall rainfall is typically from thunderstorms which are widely scattered and quite variable.

The U.S. Geological Survey collected surface runoff data on the Little Tallahatchie River north of Goodwin Creek and on the Yocona River to the South. At these gages, the average annual runoff is approximately 20 inches/year. Surface runoff accounts for just under 40% of annual precipitation with the remainder returning to the atmosphere as evaporation and transpiration. A limited amount of runoff data from Peters Creek, which includes Goodwin Creek, were collected by the U.S. Geological Survey from March 1940 to December 1942. Peters Creek, listed in the Geological Survey records as Long Creek, has 63.3 square miles of drainage area. Goodwin Creek is an 8 square mile tributary of Peters Creek. A special study was conducted by the U.S. Geological Survey of the flood of May 27-28, 1954 (U.S. Geological Survey, 1955). It was caused by a very intense rainfall centered in the Peters Creek area. Peak discharge determinations were made and published for many of the tributaries of Peters Creek including one in Goodwin Creek. Rainfall amounts, up to a maximum of 10 inches, came in a very short period of time with the bulk of it in about 2 hours. Peak runoff rates from small watersheds of 0.3 to 30 sq. miles ranged from about 1,000 to 2,000 cubic feet per second (cfs) per square mile to a maximum of about 3,000 cfs per square mile on Caney Creek about 3 miles southeast of Eureka Springs (drainage area 4.85 sq. mi.).

8.1.3 Soils

The Goodwin Creek watershed soils are primarily silt in texture and are easily eroded especially when surface cover is removed. Almost all of the watershed soils erode as primary particles with very little aggregation. High erodibility has contributed to historic development of extensive gullies in some areas that have been cultivated. Many of these gullies have very high sediment yields today.

Two major soil associations are present in the Goodwin Creek Watershed. The Collins-Falaya-Grenada-Calloway association is presently

mapped in most valleys. These are silty soils with soil-water properties ranging from poorly drained to moderately well drained. The Collins and Falaya soils developed in alluvium on flood plains, whereas the Grenada and Calloway soils usually cap valley terraces or nearly level to moderately sloping valley sideslopes. The Loring-Grenada-Memphis association occurs on ridges and hillsides. These are well drained to moderately well drained soils developed on gently sloping to very steep slopes in thick loess. The latter association includes most of the pasture and wooded area in Goodwin Creek plus some upland cropland. The former includes most of the cultivated area in the watershed. Figure 33 and Table 5 in Section 8.4 show the distribution of these soils in the Goodwin Creek Watershed.

A brief description of these soils is given here, a more complete description is given in Appendix F. Internal drainage characteristics and infiltration rates are described in Appendix H. Most of the soils are described by the Soil Conservation Service (USDA-SCS, 1963).

Calloway Series - The Calloway series is a somewhat poorly drained, strongly acid or medium acid silt loam soil formed in thick deposits of loess on upland and terrace positions. A fragipan is present, generally at a depth of 16 inches.

Collins Series - The Collins soils are moderately well drained, strongly to medium acid, that have formed in silty alluvium on nearly level bottom lands. These silt loam soils occur primarily along the stream in the bottom area and are the location of much of the cultivation in the watershed. Cotton has been the predominant crop but has been supplanted somewhat in recent years by soybeans.

Falaya Series - The Falaya series consists of somewhat poorly drained, strongly to very strongly acid silt loam soils that developed in silty alluvium on nearly level bottom land. Most of the Falaya is cultivated.

Grenada Series - The Grenada series consists of moderately well drained, strongly to very strongly acid silt loam soils that have developed in thick loess deposits on upland and terrace positions. A fragipan is present in this soil at a depth of about 24 inches.

Gullied Land - This land consists of areas that are severely eroded, severely gullied, or both. In Goodwin Creek it is all silty land with loessial material ranging in thickness from 2 to 15 feet. The surface soil and much of the subsurface soil has been washed away. Most of this is land that was cleared, cultivated and later abandoned. It is now in trees, idle or pastured and is unsuited for cultivation.

Loring Series - The Loring series includes moderately well drained to well drained, strongly to very strongly acid silt loam soils that developed in thick loess on uplands. A fragipan occurs at a minimum depth of about 30 inches.

Memphis Series - The Memphis series consists of well-drained, strongly to very strongly acid silt loam soils that developed in thick loess on uplands. In Goodwin Creek this soil occurs as a mixture with the Natchez and Guin or the Loring Soils. This soil has no fragipan within the usual depth of characterization and is predominantly wooded.

8.1.4 Land Use and Description

The drainage areas of Goodwin and Johnson Creeks are composed entirely of rural-agricultural lands. There are no incorporated towns or villages in the watersheds. Farm homes and rural residences are distributed throughout the area. Most of the roads are gravel but passable throughout the year.

Cotton and soybeans, the principle agricultural crops in the area, are grown on most of the cultivated lands. Comparatively smaller acreages of corn and small grains are planted each year. Most of the cultivated land is located in creek bottoms and on relatively flat uplands. Pasture and forest lands are usually located on moderate to steep slopes and on severely eroded uplands. Figure 34 and Table 6 in Section 8.4 show the distribution of land uses in the Goodwin Creek Watershed.

8.1.5 Geology and Description

The Peters Creek Watershed lies partially within the North Central Hills physiographic subprovince on the east and partially within the Bluff Hills subprovince on the west. Peters Creek is a tributary to the Yocona River which parallels the southern Panola County boundary. The Yocona River exits the Bluff Hills into the Mississippi Alluvial Valley about 4 miles west of its confluence with Peters Creek.

The western portion of the 87 square mile Peters Creek Watershed area is blanketed with layers of loess which thicken to the west. The uppermost loess, the Peoria, is continuous in the uplands whereas the two older loess deposits, the Roxana and Loveland, are discontinuous. The eastern portion, (about ¼ of the watershed) has a thin veneer of loess which is broken more often than not by gullies and tributary valley incisions into the underlying materials. The valleys are filled with alluvium of fairly recent origin, mostly derived from erosion of the adjacent loess covered hills of low to moderate relief.

The subsurface of most of the upland areas consists of alluvial gravels and sands with some clay lenses. Figure 30 shows a map of the geology of the area as described by Vestal (1956). Investigations by personnel of the USDA Sedimentation Laboratory over the past four years have determined that the material shown as Eocene in the eastern portion of the map is actually much younger alluvium, see Appendix E. The entire geologic assemblage of sands, gravels, and clay lenses lies above a well-developed erosion surface developed on Tertiary marine shales and mudstones. The alluvial material in the valley presently mapped as undifferentiated Holocene deposits occur in the same predictable stratigraphic sequence of lithologies throughout the entire area. These units are described in the following Geomorphic Features.

8.1.6 Geomorphic Features

The present-day channel system of Goodwin Creek is well incised into Holocene valley-fill deposits. Channel morphology has been and is influenced by the valley fill deposits. Seven valley-fill deposits have been identified; they are, from youngest to oldest (surface to increasing depth): (i) post-settlement alluvium, (ii) young paleosol, (iii) channel fill, (iv) old paleosol, (v) channel lag deposits, (vi) bog-type materials, and (vii) consolidated sandstones. Two older deposits have been found but they are presently undifferentiated. Post-settlement alluvium, produced in historic times largely by man's activities, overlies young paleosol (where present) or old paleosol materials. The young paleosol materials include both vertical and lateral accretion deposits which are less intensively weathered than are the old paleosol materials. Deposition of young paleosol materials began about 3,000 years before present (yr BP). Channel

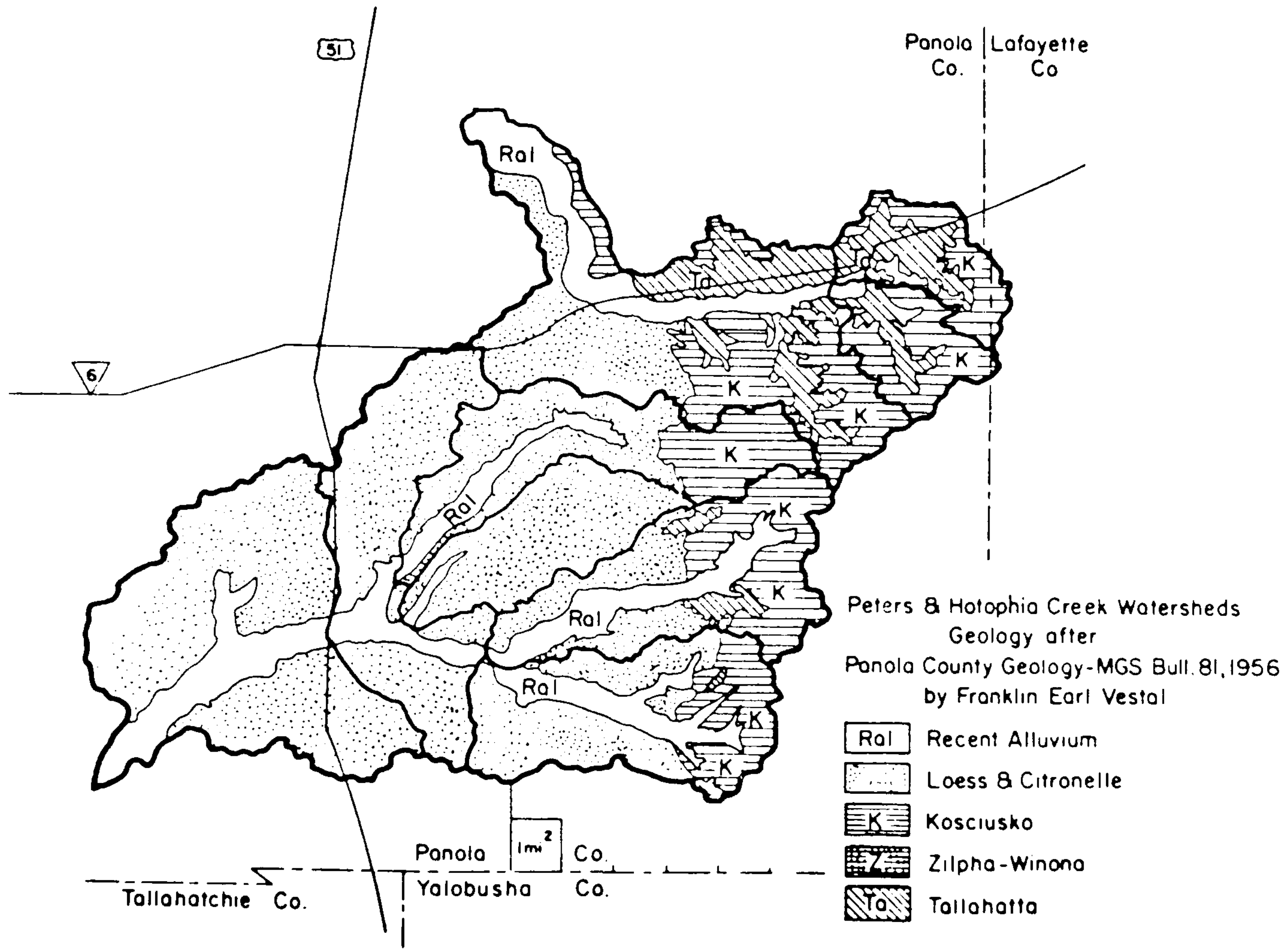


Figure 30 Geologic Map, Peters Creek, Panola Co., MS

fill deposits are not extensive; they record channel incision and subsequent filling at about 5,000 yr BP. Old paleosol materials are vertical-like accretion deposits, probably deposited during times of restricted surface drainage and low flow velocities. These materials are highly weathered. They were deposited immediately after deposition of the bog-type or channel lag deposits, both of which were deposited about 10,000 yr BP. These latter two are both fluvial deposits, but reflect differing energy regimes. The coarse-grained channel lag deposits appear to be primarily bar deposits, probably point-bar deposits, whereas the fine-grained bog-type deposits may represent materials which accumulated in channel cutoff or in separation zones downstream of channel bendways. Two deep organic deposits have been sampled but at this time are poorly defined. Both occurred in the easternmost part of our study area, at locations where the consolidated sandstone was absent. One sample at a depth of 55 feet was dated at 34,900 yr BP and the second at a depth of 45 feet was dated at 17,000 yr BP. Consolidated sandstones occur as discontinuous bodies representing scattered remnants of one or more sedimentary units older than 40,000 yr BP. A total of 115 organic samples have been dated thus far.

The nature and chronology of these deposits and their fit with the paleoclimatic record indicate that the dominant controls of the valley-fill sedimentary system has been the paleoclimate and concurrent base level conditions. In this scenario, mid to late-Wisconsin times were characterized by widespread stream incision controlled primarily by low base level. This interpretation is based upon the relative paucity of pre-Holocene organics, the extreme depth of the few organic samples older than Holocene and the presence of early-Wisconsin loess capping of present-day valley terraces. As the late-Wisconsin glaciation waned and sea levels rose, valley degradation ceased and aggradation began. Post-glacial fluvial conditions resulted in increased fluvial deposits such as the channel lag and bog-type deposits about 10,000 yr BP. Tributary valleys rapidly became plugged, inducing deposits of old paleosol materials. The source of these sediments was the interfluve loess. Valley aggradation ceased as the climate became drier and this condition persisted until about 6,000 yr BP. Fluvial activity was renewed at this time as evidenced by the channel fill deposits. At about 3,000 yr BP channel incision into or

through the old paleosol was accentuated by increased precipitation at this time, and young paleosol materials were deposited as a normal consequence of channel meandering and backfilling.

Four of these valley-fill stratigraphic units influence channel stability and morphology. The youngest of these units, the post-settlement alluvium (PSA), functions primarily as a loading factor for gravity-induced failure of either of the underlying paleosols. Failure of the PSA is also gravity induced. The next youngest of these units is the young paleosol, a relatively unweathered fluvial deposit. Failure of the young paleosol material results primarily from gravity stress, and is accentuated by the development of vertical tension cracks parallel with the bank. Tension crack development is undoubtedly related to the relatively unweathered and, hence, isotropic nature of this silty material. Old paleosol materials underlie the young paleosol and/or historic sediments. They are highly weathered and are typified by a well-developed polygonal structure which controls the mode of bank failure. The polygonal seam materials have extremely low stability, and block-type failure is induced by gravity stress, following seam material wetting and removal. In general, the old paleosol materials are more stable than the younger materials. Gravel and/or sand deposits underlie the old paleosol. These deposits are usually unconsolidated but are occasionally cemented by iron, forming bed-control sills where they outcrop in the channels. Exposure of the unconsolidated materials in a bank toe position, resulting from vertical degradation, typically increases rates of failure due to gravity stress.

Present-day channel morphology in northern Mississippi has been largely determined by the presence or absence of the consolidated sandstone bed control sills. Where such sills are absent, such as in Johnson Creek, a tributary of Peters Creek, thalweg lowering has progressed to a sufficient depth to expose the unconsolidated gravels and/or sands in a bank toe position. For this condition, gravity forces become the limiting stress for bank stability. Thalweg degradation in Johnson Creek started at least 40 years ago and has progressed upstream in the form of either a diffuse or discrete knickpoint. Channel width-to-depth ratios are coherent upstream of the knickpoint where the channel bed material is either of the cohesive paleosols. Downstream of the knickpoint, however, Johnson Creek is a sand-bed channel and measured channel depths are less than scour hole

depths. Width-to-depth ratios are random downstream of the headcut, resulting from excessive channel widening particularly in young paleosol materials.

Where iron-cemented sills have prevented vertical degradation, such as in Goodwin Creek, a gravel-bed tributary of Peters Creek, excessive lateral channel erosion has occurred. This widening is not constant throughout the system but a definite width/depth ratio appears to be associated with local stratigraphic and/or channel morphometric conditions (see Appendix E). Channel sinuosity is also highly variable, but is associated with natural bed control sills and obviously provides form roughness in the form of large bendways. Selected reaches in both channels have widened excessively since 1968.

In summary, energy expenditure within the channels has not been uniform over relatively long channel lengths but has been concentrated in relatively short reaches of the channel. As illustrated for Johnson and Goodwin Creeks, this form of degradation is intimately associated with the nature and distribution of the valley-fill stratigraphic units of Holocene age. Channel morphology and channel morphometric changes are similarly intimately associated with these Holocene units. Gravity stresses limit bank stability for channels which are presently incised and the magnitude or rate of failure ultimately depends upon the ability of the flow to remove the slough from the bank toe position. Slough from either of the paleosols and from the post-settlement alluvium is easily removed, regenerating the failure process.

8.2 CHANNEL STABILITY PROBLEMS IN GOODWIN AND JOHNSON CREEK WATERSHEDS

8.2.1 Basic Concepts

Most of the concepts underlying an evaluation plan for a watershed were discussed in Chapter 6. However, to prevent or minimize any ambiguity, they are restated below emphasizing the concepts that apply to problems in the Goodwin and Johnson Creek Watersheds.

8.2.1.1 Channel Stability: The terms, stable and unstable are nebulous, by themselves, especially when applied to channels. All channels are subject to change, these are evaluated as acceptable or unacceptable based

on socio-economic and time constraints. If the rate or magnitude of change is unacceptable, the channels are classified as unstable. This classification of stable versus unstable is, in essence, independent of the stream system characteristics.

8.2.1.2 An Idealized Stream (fluvial) System: Schumm (1977) describes an idealized fluvial system which has utility in identifying elements of channel stability. In simple form, the idealized system has three zones. The headward-most zone, Zone 1, is the area of sediment and water production. By definition, this is a zone of erosion and temporary storage of sediment. The middle zone, Zone 2, is the transfer zone. Channels in this zone are at grade if sediment input equals sediment output. The lowermost zone, Zone 3, is the area of deposition. Aggradation occurs in this zone. Thus, both aggradation and degradation will occur simultaneously in any one complete system, but not necessarily in a given watershed. Channels in the transfer zone will be at grade for a stable system but such channels may be unstable based upon socio-economic criteria.

8.2.1.3 Watershed System Changes: Inherently, Zones 2 and 3, in the system discussed by Schumm (1977), depend greatly on the condition of Zone 1. Changes in either or both sediment and water production and/or routing will induce changes in Zones 2 and 3. The dominant control may be either intrinsic or extrinsic and may effect changes within zones or may cause the boundaries between zones to change. An extreme example of the latter type of change is that produced by the concurrent paleoclimatic and base level change at the Holocene-Wisconsin (time) boundary. Other factors responsible for change include land use changes, channel improvement and water-handling structures which can cause changes in the timing of flood peaks.

8.2.1.4 The Complex Watershed System: Frequently, secondary systems are imposed upon the idealized stream system of Section 8.2.1.2. Two types of secondary systems have been observed. Excessive sediment production in Zone 1 may form a large sediment wave. Such waves, equivalent to a small scale Zone 3, move downstream, effecting channel changes. The second type involves knickpoint migration upstream. The knickpoints, equivalent to a small scale Zone 1, similarly effect reach changes but such changes migrate upstream ultimately resulting in excessive sediment production. This type of complex response is typical in many Bluff Area streams.

8.2.1.5 Classes of Channel Stability: The classes of instability (total stream system, reach and point), discussed in Chapter 6, are an attempt to more-definitively classify channel changes. The classification also has utility for channel improvement activities. Total stream system instability is typified by bed elevation changes, throughout all three zones of the system. Generally, the channel system must be modified significantly before bank stability can be achieved. Local bank protection measures will only transfer problems from one point to another. This type of system instability represents a total imbalance between hydraulic erosive forces and bank material strength over a period of many years. Point instability, on the other hand, typifies a relatively stable system. The channel bed is stable and bank failure results from atypical local conditions. This type of failure can be alleviated by standard bank protection measures, if such is deemed necessary. Reach instability represents the middle area between the two extremes. The system is marginally stable, some reaches are stable and some are not. If the positions of the stable and unstable reaches are constant through time, noted as static reach instability, failure most probably is the result of channel morphometric conditions or relatively weak bed or bank materials. Failure mechanisms must be ascertained to evaluate (i) potential rates of change and (ii) the probability of natural healing. Migrating unstable reaches, noted as dynamic reach instability, typify complex systems and must be evaluated accordingly. Knickpoint migration is particularly detrimental in that it may result in both static reach instability downstream of the knickpoint and ultimately excessive sediment production from Zone 1 as the knickpoint moves upstream. Such knickpoints are obviously detrimental to the stability of the system and must be controlled before overall system stability can be achieved.

8.2.2 Channel Stability in Goodwin and Johnson Creek Watersheds

Evaluation of channel stability problems in Goodwin and Johnson Creek Watersheds was implemented to describe channel stability problems in accordance with the preceding concepts. The most important aspect of the evaluation was a comprehensive field survey to define (i) the locations of bed and/or bank failures in the watersheds; (ii) the mechanisms of failure; (iii) association between failure mechanism, location, and valley-fill (stratigraphic) unit and (iv) general conditions of vegetative bank cover, bed roughness, bed material size, etc. Historic changes in bank conditions

were evaluated using ASCE photographic records which date to 1937 for the study area. Based upon the field and photo inspection, we classified both Goodwin and Johnson Creek channels as follows:

a. Neither system is totally unstable. Both are characterized by stable reaches separated by reaches with bed and/or bank failure problems.

b. Both systems have point instability problems of three general types.

1. Atypical roughness elements, usually trees which have fallen into the channel; the locations of these have a stochastic distribution.
2. Seep-induced bank failure, which typically occurs at the interface between the relatively permeable young paleosol and the less permeable old paleosol. The interface is an erosional surface at many locations and has the potential for developing excessive seep forces. Ice lenses have been observed at this interface.
3. Paleochannels filled with coarse materials of low cohesion have minimum resistance to gravity stress and fail rapidly. This type of failure is usually not progressive and the failure point will stabilize with time because of the relatively coarse texture of these materials.

These types of point instability may become locally critical to landowners if they capture sufficient drainage area. Massive "blowouts" can result from overbank flow into the channel via such point failures.

c. Both Goodwin and Johnson Creeks have reach instability problems. The Goodwin Creek channel exhibits static reach instability typically associated with reaches of excessive sinuosity. At several locations, the flow appears to have "bounced" from old paleosol bank exposures and rapidly eroded into young paleosol materials. The bed of Goodwin Creek has been relatively stable due to the presence of consolidated sandstone sills and a large amount of gravel in the bed material. The lowermost sill on Goodwin Creek has failed, however, and thalweg lowering occurred for a distance of about 4000 feet. In contrast, the Johnson Creek channel exhibits migrating reach instability in the form of a knickpoint. This knickpoint is identifiable on the 1937 aerial photograph and has moved upstream at an

average rate of 500 to 600 feet per year. At times, the knickpoint followed a dredged canal and at other times it followed the original channel. The knickpoint effectively separates Johnson Creek into two distinctly different reaches. Upstream of the knickpoint, the bed and banks are composed of cohesive paleosol materials. Bank failure is rare and the channel bed is stable. Downstream of the knickpoint, the channel has a sand-to-gravel bed. Bed stability is controlled by the sediment and water yield characteristics of Zone 1. Bed lowering, sufficient to expose the unconsolidated bog-type or channel lag deposits, has induced massive, gravity type bank failure (see 8.1.6). The resultant bank slough is fine textured and easily removed by channel flow, regenerating the gravity-induced failure process.

8.3 GRADE CONTROL AND OTHER DEVICES IN GOODWIN AND JOHNSON CREEK WATERSHEDS

Channel stability problems in Goodwin and Johnson Creek Watersheds (see Section 8.2) led to construction of a variety of grade control and other stabilization structures. A complete discussion of these structures is presented in Appendix A. In addition to structural measures, several different vegetative schemes have also been installed. These are discussed in Appendix C.

8.3.1 Goodwin Creek Grade Control Structures

The channel on Goodwin Creek has enlarged so much that it is alienated from its flood plain over several reaches, to the point that overbank flow is almost nonexistent. In these sections massive bank failure is evident as described previously. In order to help stabilize some of these reaches, grade control structures have been placed on many of the channels in the Goodwin Creek catchment. The amount of fall removed in the structures was based on the degree of incision at that point. The structures were also designed to act as flow measuring and sampling sites. Details of construction in relation to instrumentation are presented in Appendices A, B and F.

Stabilization using vegetative schemes are also being investigated on Goodwin Creek. These are described in Appendix C.

8.3.2 Johnson Creek Stabilization Program

The channel on Johnson Creek has deteriorated over the past 40 years as a headcut moved up through the watershed. This is discussed in Section 8.2 and Appendix E. The extremely large and unstable channel is the site of several types of structural and vegetative projects. Three minimum cost grade control structures are located at the upper end of the eroding channel. Hopefully they will prevent further upstream migration of the channel instability. Just upstream from the downstream structure about 2200 feet of the channel are protected by a combination of bank forming, toe revetments and vegetative treatments. These studies were initiated prior to completion of the grade control structures and delay in construction of the grade control structures created several problems with loss of toe protection. However, the study is still a very informative one and is providing good information on the different treatments. See Appendices A and C for a more complete discussion of these treatments.

In a channel reach downstream from the grade control structures, minimum toe revetment, in the form of rock riprap, is being used to control further bank failure and provide a stable bank for establishment of vegetation. In general, the scheme has worked although some failure, where flow was able to get behind the stone, has been observed.

In the lower reaches of the channel a slotted board fence was installed to protect a high, very sharp bend and prevent cutoff of a road bridge. The fence appears to have stopped erosion of the bank but redirected flow is creating problems on the opposite bank downstream.

The channel reach between the board fence and the minimum toe revetment upstream is a stable reach about 3 miles long. It experienced knickpoint movement about 30 years ago, but has since become a naturally vegetated channel with stable banks. The channel is large enough that it does not experience over bank flow; however, it appears to have developed a smaller channel within the larger one. This reach is being monitored for any change in its apparent stability. For further discussion of the structural and vegetative studies on Johnson Creek, see Appendices A and C. For further discussion of the stable reach see Appendices A and E.

8.4 THE GOODWIN CREEK WATERSHED STUDY

The Goodwin Creek Watershed is part of the field phase of the channel stability project. The objective in selecting Goodwin Creek was to select a bluff line watershed with channel instabilities that would have grade control structures installed. The watershed was to be instrumented with sensors to measure streamflow, sediment transport, and related variables. The sensors were installed to measure the response of typical land use and soils areas and the influence of the grade control structures and upland watershed processes on the channel system and the transport of sediment. Data is now being collected on climatic conditions, soil moisture, groundwater levels, erosion rates, and surface water movement from major land uses, soils, and geologic areas in the watershed.

8.4.1 Criteria for Selection of Goodwin Creek Watershed

The criteria used in the selection of the research watershed included:

1. It must be a bluff line tributary, 10 to 50 square miles in size in the Yazoo Basin.
2. It must have a range of channel conditions and sediment source areas.
3. It must not drain into one of the existing Corps of Engineer reservoirs.
4. It must be sufficiently close to the research headquarters to allow effective guidance of field data collection and research.
5. It should have a variety of soils and land uses that include cultivated, pasture, and wooded areas.
6. The downstream reach should not have a major tributary and be suitable for sediment routing studies.

Conditions 1, 3, and 4 led to the selection of the area shown in Figure 29. Conditions 2, 5, and 6 led to the selection of Goodwin Creek, one of the tributaries of Peters Creek, as the intensively instrumented research watershed. A more limited set of information for a study of vegetative control of streambank stability is being collected on Johnson Creek, a tributary immediately north of Goodwin Creek.

8.4.2 Goodwin Creek Drainage Areas, Soils and Landuse

Goodwin Creek has approximately equal pastured, cultivated, and wooded areas. It has a variety of channel conditions and sediment source areas.

Figure 31 is a topographic map of the watershed area. The watershed was divided into subwatersheds to isolate different channel types, sediment source areas and land uses. Figure 32 shows the location of subwatersheds located within the Goodwin Creek Catchment. The drainage areas of the subwatersheds are shown on Table 4.

The reach between Stations 1 and 2 is suitable for routing water and sediment because of few intervening tributaries. Station 9 is formerly heavily gullied and has some of the highest rates of sediment yield in the watershed. Station 10 is entirely wooded while Station 11 has no cultivated and very little wooded area. Stations 13 and 14 have very large bed material with sizes ranging up to large gravels.

Soils in the Goodwin Creek Watershed were described in Section 8.1.3. A map of the distribution of the soils within the Goodwin Creek Catchment is shown on Figure 33. Table 5 gives the percentage distribution of soil type within each subwatershed.

A general landuse map of the Goodwin Creek drainage area is shown in Figure 34. Four broad landuse classifications - cultivated land, pasture, forest, and idle land are shown. Land not being used for crops, pasture, or forest at the present time, 1980, was placed in the idle category. Land use for the Johnson Creek watershed is essentially the same as that in the Goodwin Creek Watershed. The map was prepared to show a general picture of land use. Watershed and field boundaries are approximate and should not be used for determining watershed and field areas. Not shown are approximately 90 farm ponds which exert some hydrologic control over a significant portion of the watershed. Active sediment producing gullies occur throughout the watershed but the number and aerial extent of these has not been determined. Table 6 summarizes the approximate percentage of land use in each subwatershed.

8.4.3 Goodwin Creek Waters[illegible] Collection Facilities

An important part of this project is the collection of field data to assess the affect of channel stability measures and upstream practices on the channel system and sediment transport. The data needed to make this assessment include runoff rate, sediment transport rate, characterization of sediment sizes, land use, soil moisture, precipitation, and other climatological data such as solar radiation, evaporation, wind, water and air temperature.

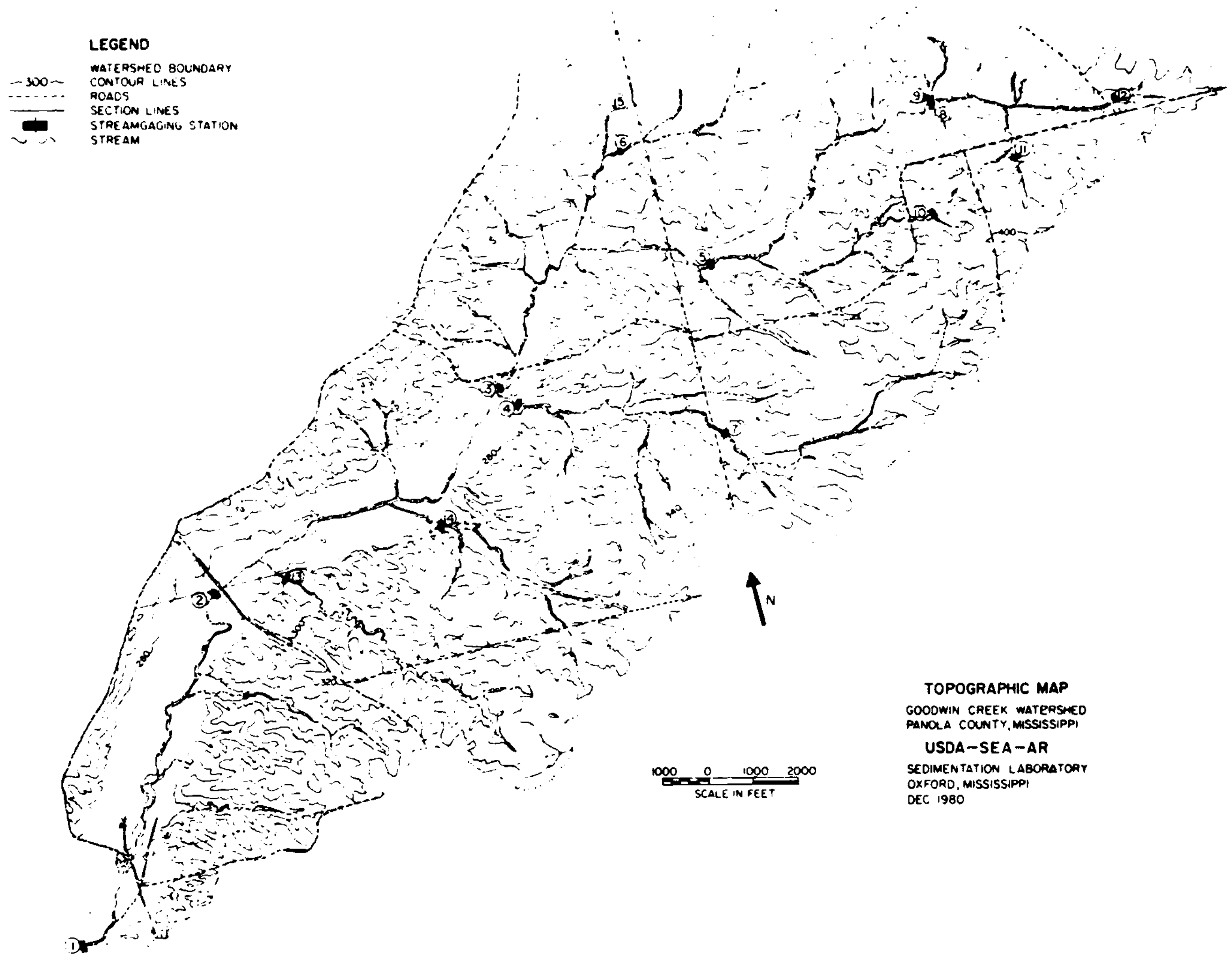


Figure 31 Topographic Map, Goodwin Creek, Panola Co., MS

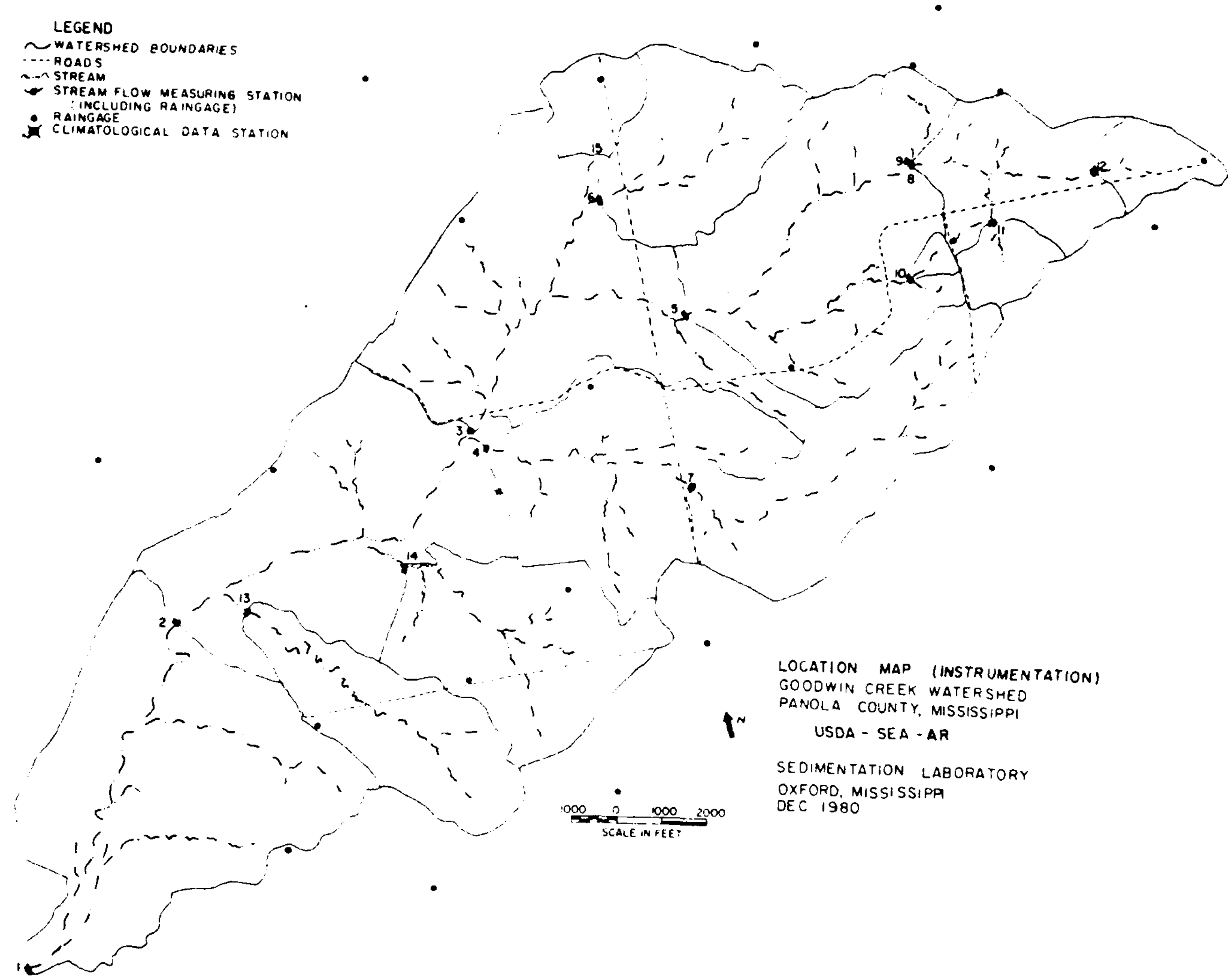


Figure 32 Instrumentation Location Map, Goodwin Creek, Panola Co., MS

Table 4 Subwatershed Drainage Areas in Goodwin Creek Catchment

Watershed	Drainage Area (Acres)	Drainage Area (sq.mi.)
1	5286	8.26
2	4430	6.92
3	2172	3.39
4	880	1.38
5	1061	1.66
6	298	.46
7	399	.62
8	384	.60
9	45	.070
10	15	.024
11	69	.108
12	74	.115
13	304	.48
14	403	.63
15	89	.39

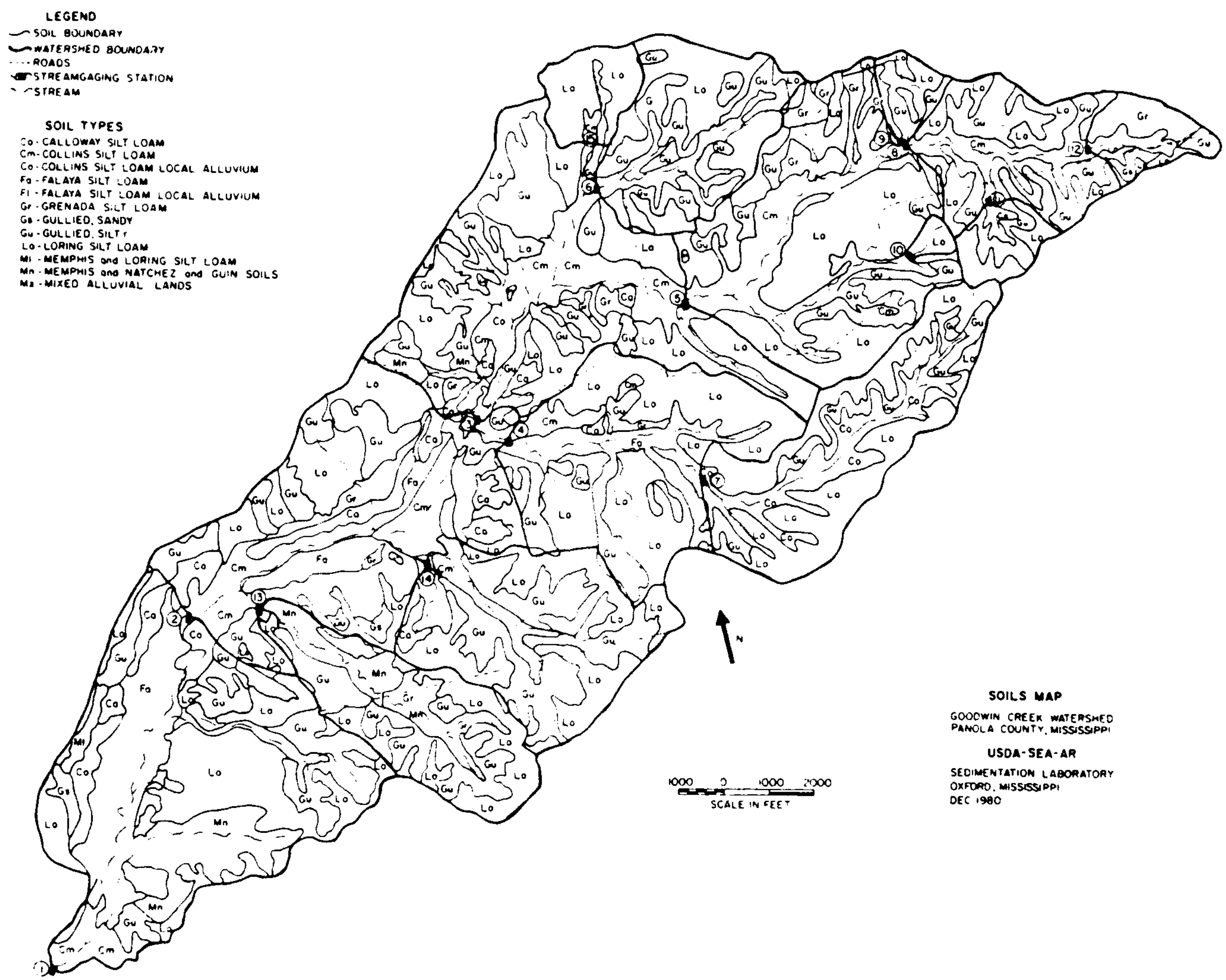


Figure 33 Soils Map, Goodwin Creek, Panola Co., MS

Distribution of Soil Types in the Goodwin Creek Catchment

Watershed Number	Drainage Area (sq.mi.)	Soil Types 1/											
		Ca	Cm	Co	Fa	Fl	Gr	Gs	Gu	Lo	Ml	Mn	Mx
[illegible]	8.26	5	13	5	9	*	4	1	24	34	1	4	*
[illegible]	6.92	4	14	5	7	*	5	*	27	36		2	*
[illegible]	3.38	2	22	3			7	*	27	38		1	
4	1.38	1	6	16	5	1		1	25	46			
5	1.66		22	1			9		27	40			
6	.46		16				2		38	44			
7	.62			28					18	54			
8	.60		21	4			9	2	32	32			
9	.070						13		47	40			
10	.024		2							98			
11	.108		13						39	48			
12	.115		1	17			41	9	24	8			
13	.48			2			11		40	30		17	
14	.63	2	15						45	38			
15	.139	6	9						2	83			

Values are percentage of watershed area in soil type

1/ Key to soil type
Ca - Calloway Silt Loam
Cm - Collins Silt Loam
Co - Collins Silt Loam, Local Alluvium
Fa - Falaya Silt Loam
Fl - Falaya Silt Loam, Local Alluvium
Gr - Grenada Silt Loam
Gs - Gullied Land, Sandy
Gu - Gullied Land, Silty
Lo - Loring Silt Loam
Ml - Memphis and Loring Silt Loam
Mn - Memphis, Natchez, and Guin Soils
Mx - Mixed Alluvial Land

*Soil type present but less than .5% of area

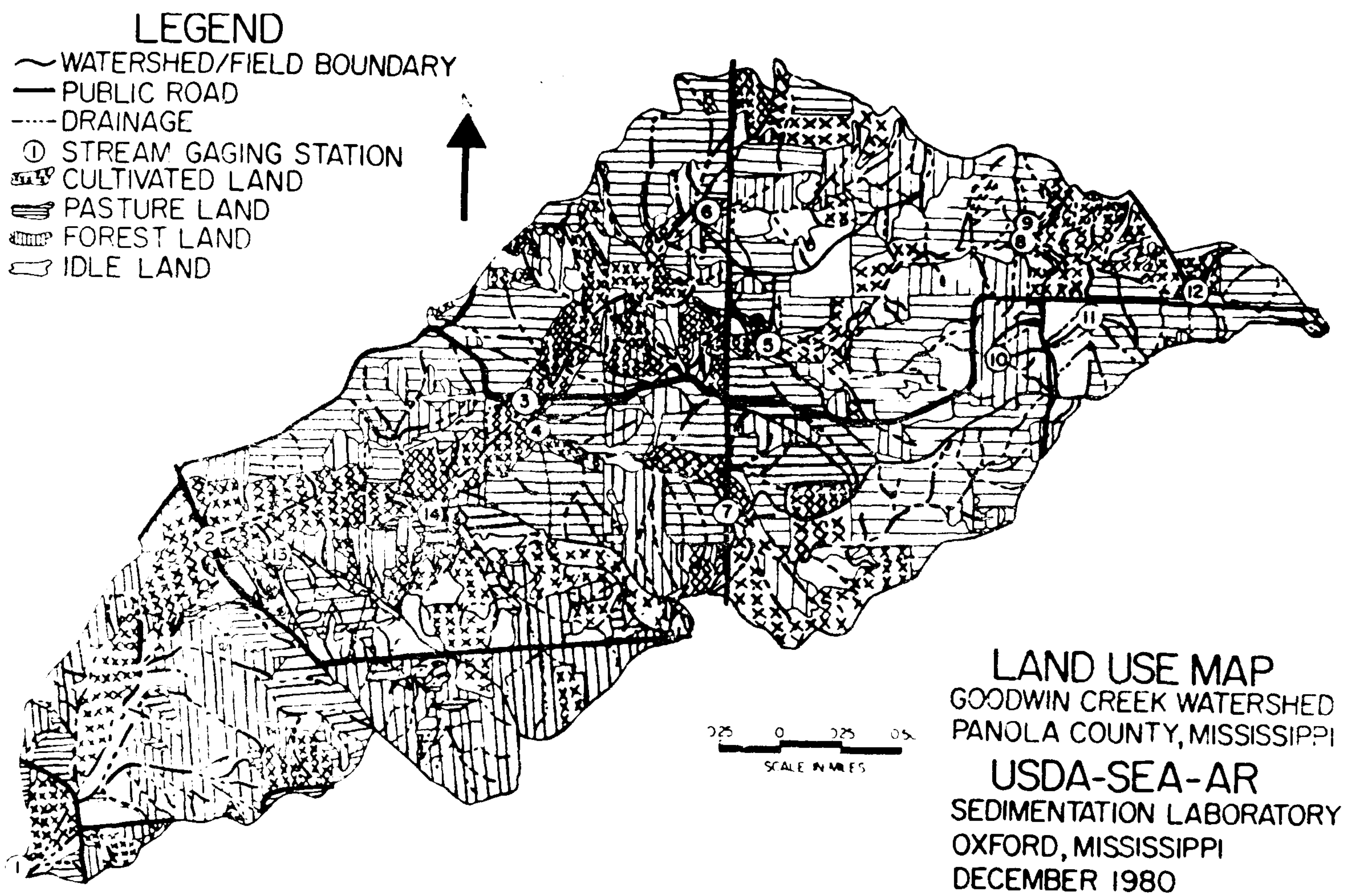


Figure 34 Land Use Map, Goodwin Creek, Panola Co., MS

Table 6 Distribution of Land Use in the Goodwin Creek Catchment

Watershed	Drainage Area (sq. mi.)	Idle (%)	Wooded (%)	Pasture (%)	Cultivated (%)
1	8.26	8	27	30	35
2	6.92	7	26	31	36
3	3.39	8	21	33	38
4	1.38	2	21	41	36
5	1.66	10	20	35	35
6	.46	8	28	30	34
7	.62	3	4	56	37
8	.60	16	3	48	33
9	.070	10	60	30	0
10	.024	0	100	0	0
11	.108	69	7	24	0
12	.115	0	0	83	17
13	.48	24	49	27	0
14	.63	4	43	6	47
15	.139	22	0	0	78

The Goodwin Creek Watershed has been instrumented and sensors to collect much of this data have been installed. Figure 32 is a location map of the watershed instrumentation. A variety of data are collected at the streamflow measuring stations, each located at a grade-control structure. These data are summarized in Table 7. The details of each type of sensor are given in Appendix F, but a summary of the data collected is given below.

Runoff data are measured indirectly. The water level in the grade control structures is measured and a rating used to compute the discharge rate. The rating is theoretical and based on the geometry of the grade control structure and estimated resistance coefficients. As discharge measurements of flood flow are made, the ratings will be verified and updated as needed. Precipitation is measured in the vicinity of each streamflow station with a weighing recording raingage. Sediment-laden water is pumped from the stream through a density cell, and the flow from the density cell periodically routed to a sediment sampler. The density cell gives a voltage output which has been laboratory calibrated against sediment concentration. The samples collected from the sediment sampler are taken back to the laboratory and analyzed for concentration and particle size distribution. Water temperature is measured with a thermister located in the pool just downstream of the structure. Air temperature, also measured by a thermister, is monitored in a louvered shelter located on the streambank by the structure. Soil temperature is measured on the streambank in the fenced enclosure for the instruments; the depths are shown in Table 7.

Most of the data are collected by sensors which give an electrical output; this output is held in temporary storage at the field station and sent back to a central computer by VHF radio. The system of data acquisition was chosen after considering several options. The traditional method of using mechanical recorders and bringing charts in by courier has the disadvantage of high labor requirements, especially in getting the data into a digital form. Magnetic tape recorders at each site would have eliminated the digitizing requirements but revealed nothing until the site was visited. Radio telemetry was selected to ease the transfer of data to a digital form, improve data quality by providing a common time base for all data on the system, and aid in field maintenance by giving a real time picture of the watershed data response.

Table 7 Goodwin Creek Watershed Instrumentation

A. Flow Measuring Stations

Data Type	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Depth of flow	M	X	X	X	X	X	X	X	M	X	M	X	M	M	M
Precipitation		X	X	X	X	X	X	X		X		X			M
Density cell (Sediment conc)		X	X	X	X	X	X	X				X			
Pumped sediment samples		X	X	X	X	X	X	X		X		X			
Water temperature		X	X	X	X	X	X	X		X		X			
Air temperature		X	X	X	-	-	-	-		-		X			
Soil temperature		X	X	X	X	X	X	X		X		X			

X Data collection electronically

M Data collection by chart

\- No sensor planned

B. Climatological Data Station (Site 50)

1. Standard precipitation
2. Ground level precipitation
3. Wind speed
4. Wind direction
5. Humidity
6. Barometric pressure
7. Air temperature
8. Evaporation pan level
9. Evaporation pan - wind speed
10. Evaporation pan - temperature
11. Solar radiation

The system consists of a central laboratory computer and 12 field stations (Two of the field stations are double stations each serving two streamflow sites). Each field station is a micro-computer with VHF radio and radio interface. The data collected at a site are stored in the micro-computer memory at intervals of up to one observation a minute. Every 30 minutes the central computer sends a poll message requesting the stored data be transmitted. The transmitted data are then stored on disk at the central computer until removed for processing.

The runoff and precipitation data at streamflow stations are also collected on charts. These charts are back up to the telemetry system and are processed if the telemetry system is down or a data station is not working. Field maintenance personnel visit each site routinely once a week to check the instrumentation and change charts. More frequent visits are made during storms to make discharge measurements and collect sediment samples by hand.

8.4.4 Hydrologic Data Reduction

The data are brought from the field to the laboratory in a variety of forms; as traces on a chart, map notations, radio messages, or observations in a notebook. To be readily usable the data must be converted to a digital form, reduced, edited, and stored on a computer. Much of the data comes directly from the field in a digital form, as radio signals. Data from nontelemetered raingages are brought in as charts. These data are converted to a digital form on a digitizer. Data from water level recorders and from raingages at telemetry sites are also brought in on charts as back up for the radio transmitted data. These charts are digitized as needed to fill in any gaps when the telemetry system is not working. Some data such as field surveys are keyed directly from field notebooks into the computer.

Once in digital form, conversion to real units is the next step. Much of the data, particularly that which is telemetered, has reached the lab as a digital form of an electrical signal. Conversion to equivalent real units is necessary before further processing. Periodic field calibration of each field sensor is made by the field maintenance technician following sensor installation. This relationship and any updated versions is stored on computer and used to convert the electrical signal to appropriate units.

Data from nontelemetry sources are merged with the telemetry data and a complete set of data is then available. At this step, the data are edited, checked for errors, and coded to indicate any special conditions. Water level data are converted to discharge by using ratings for the grade control structures.

8.4.5 The Data Management System

The goal of any data collection system is the use of that data for some benefit. To facilitate that use the data which have been collected, converted, and edited are stored in a data management system. This system is composed of several data bases and supporting software.

Martin (1976) defines a data base as "a collection of interrelated data stored together with controlled redundance to serve one or more applications in an optimal fashion; the data are stored so that they are independent of programs which use the data; a common and controlled approach is used in adding new data and modifying and retrieving existing data within the data base." Two of the concepts in Martin's book are guiding the development of Goodwin Creek data bases. These are the concept of logical and physical independence of data. The concept of logical data independence means that different users can see different logical organizations of the data without requiring different actual organizations. This allows new programs and modifications of old ones to see different data organizations. Thus the data requirement for one program can change without disrupting data organization for other programs. The concept of physical data independence means that change in how the data are stored will not affect the overall logical organization of data or the application programs which use them.

Two broad categories of data have led to two different sets of data bases. One category is data which varies slowly with time or is considered time invariant. Examples include the locations of drainage divides, the drainage network, field boundaries, land use, soils, etc. These data are stored in a spatial information system with locations based on the Mississippi Plane Coordinate System. Definition of most features in this data base are by straight line segments or polygons. The second broad category is data which may vary rapidly with time. This category includes data such as water level, streamflow rate, precipitation, sediment transport rate, etc. The major characteristic of these data are many observations for some of the sensors at a location.

The data management system consists of the collection of data and the programs for retrieval and maintenance of the data. Some types of requests occur fairly frequently. Examples include availability, maximum, minimum, range, mean, standard deviation. A user can obtain these directly without the need for his own software. A user can also write his own application programs and retrieve the data for it.

The Vicksburg District Corps of Engineers has its own data base system, the Yazoo Basin Data Management System. The Goodwin Creek data can also be put into the Yazoo Basin system and used there. The system of the laboratory is designed and oriented toward a small area, an area of a few square miles, while the Yazoo Basin System is designed to handle data for hundreds of square miles.

A more complete discussion of the Goodwin Creek data management system and its structure is given in Appendix F.

8.5 EXAMPLES OF APPLICATION OF HYDROLOGIC AND BANK STABILITY MODELS

In Chapter 7 several different models, both hydrologic and bank stability, were described. They are presented in detail in Appendices D, I, J, and K. Examples of the use of the bank stability models are presented in Appendix D. In this presentation the bank materials characteristics were measured in the field and the data used to evaluate the bank's stability. For several of the sites, the regions of stability, marginal stability, and instability are defined. A plotting of the condition of the specific site in almost all cases was substantiated by conditions observed in the field. For example, one site on Tommy Florence's farm has been observed to fail periodically. It plots in the marginally stable region on the diagram. Other examples are discussed in Appendix D.

8.5.1 Hydrologic Models

Data to test and verify the hydrologic models presented in Chapter 7 were not available from the Goodwin Creek Watershed; therefore, other hydrologic data were used to illustrate their use.

The data used for testing the single event model were obtained from the USDA experimental watersheds W-5 southwest of Holly Springs, MS, and R-5 near Chickasha, OK (Burford and Clark, 1973). Watershed W-5 drains a

1.76 square mile (4.56 km^2) area, see Figure 35, with a good mixture of cultivated timber, pasture, and idle land. Watershed R-5 has an area of 23.7 acres (9.6 ha), and is range land with an excellent native grass cover, see Figure 36. These watersheds were chosen because of diversity and availability of most of the required data. Sediment records were available for Watershed R-5, but the sediment yield was so small that no comparisons were made between measured and computed sediment discharges.

The model was calibrated using the event of February 21, 1971, on Watershed W-5, and the event of May 6, 1969, on Watershed R-5. Infiltration parameters for Watershed W-5 were estimated from information reported by Smith and Parlange (1978) for Colby swelling type soils, because very little infiltration data were available. The infiltration parameters for Watershed R-5 were obtained from an average infiltration curve obtained from a large number of infiltrometer runs conducted in the fall of 1977. The calibrations were carried out by adjusting first the flow resistance parameters to match the hydrographs, and then the sediment-model parameters were adjusted to fit the sedimentgraphs. These same parameters were used in simulating all the remaining events. During these verification runs only the antecedent soil moisture content, initial interception storage, and the initial loose soil storage were adjusted. In the next generation model, a continuous simulation system (under development), these parameters will be known.

Examples of the comparison between the simulated and the measured hydrographs and sedimentgraphs are shown in Figures 37, 38, and 39. A total of nine events on Watershed W-5 and two on Watershed R-5 were simulated. The agreement between the shapes of measured and simulated events is satisfactory. Comparisons between measured and computed water yield, peak runoff rates, sediment yield, and peak sediment discharge are given in Figures 40 and 41. These plots show that the model estimates both yields and peaks within a range of about ± 40 percent of measured values. The limited number of events used in this study precluded an estimation of the confidence level of the range of variability. The results presented in Figures 7 through 41 indicate that simulations of different size events using only one set of parameters for each watershed, were satisfactory. This suggests that the model could be used to predict the response of a catchment to different management practices, if the model parameters associated with each practice could be accurately estimated.

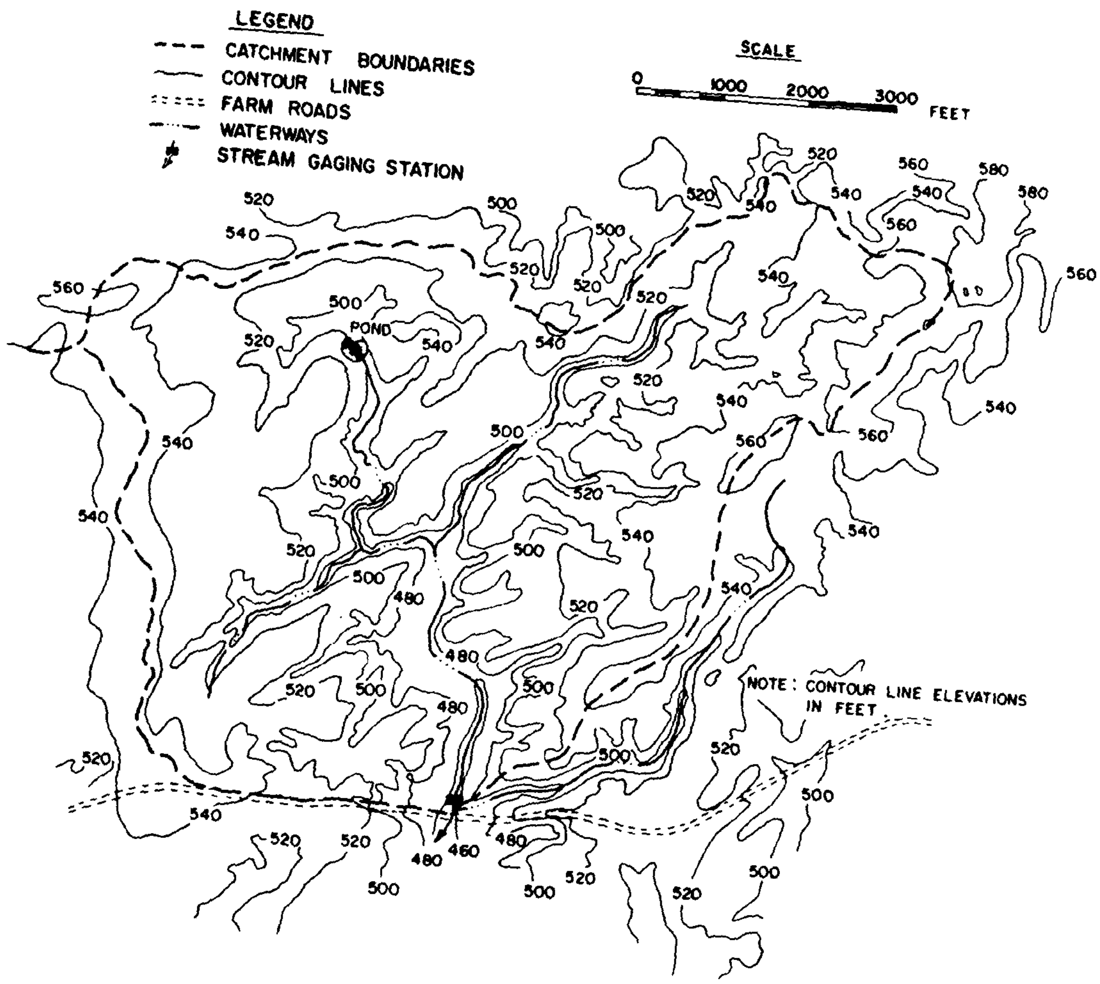


Figure 35 Topographic Map of Watershed W-5 near Holly Springs, MS

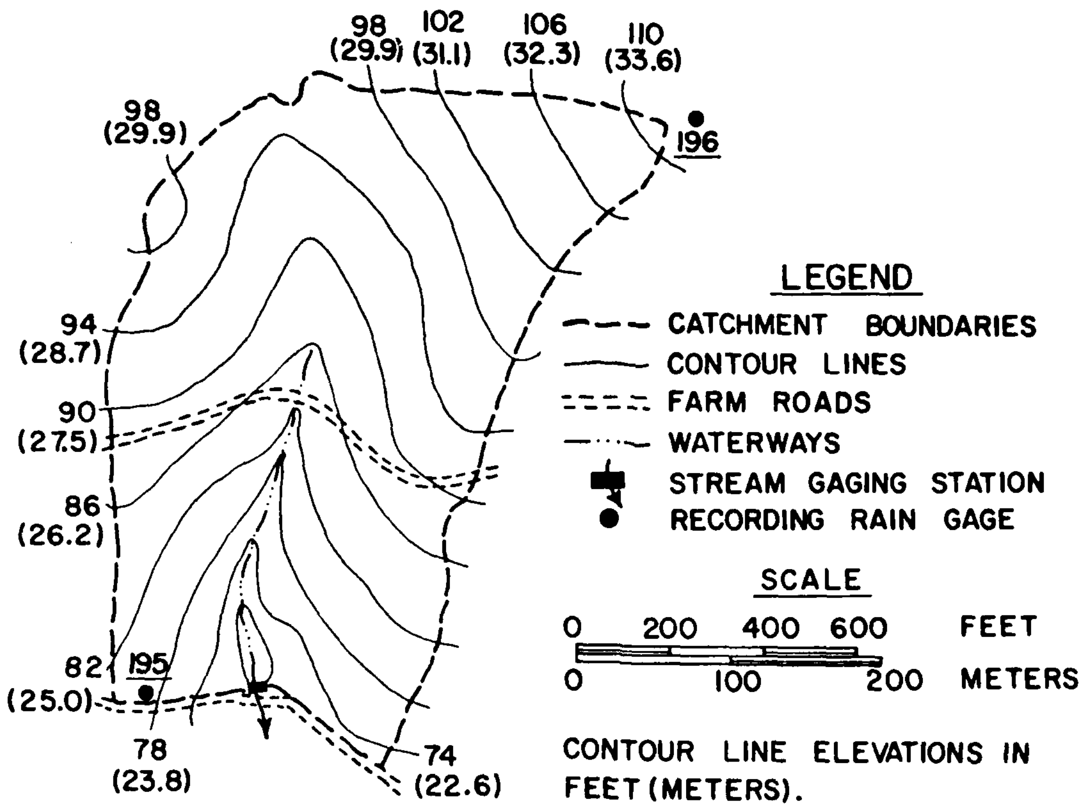


Figure 36 Topographic Map of Watershed R-5 near Chickasha, OK

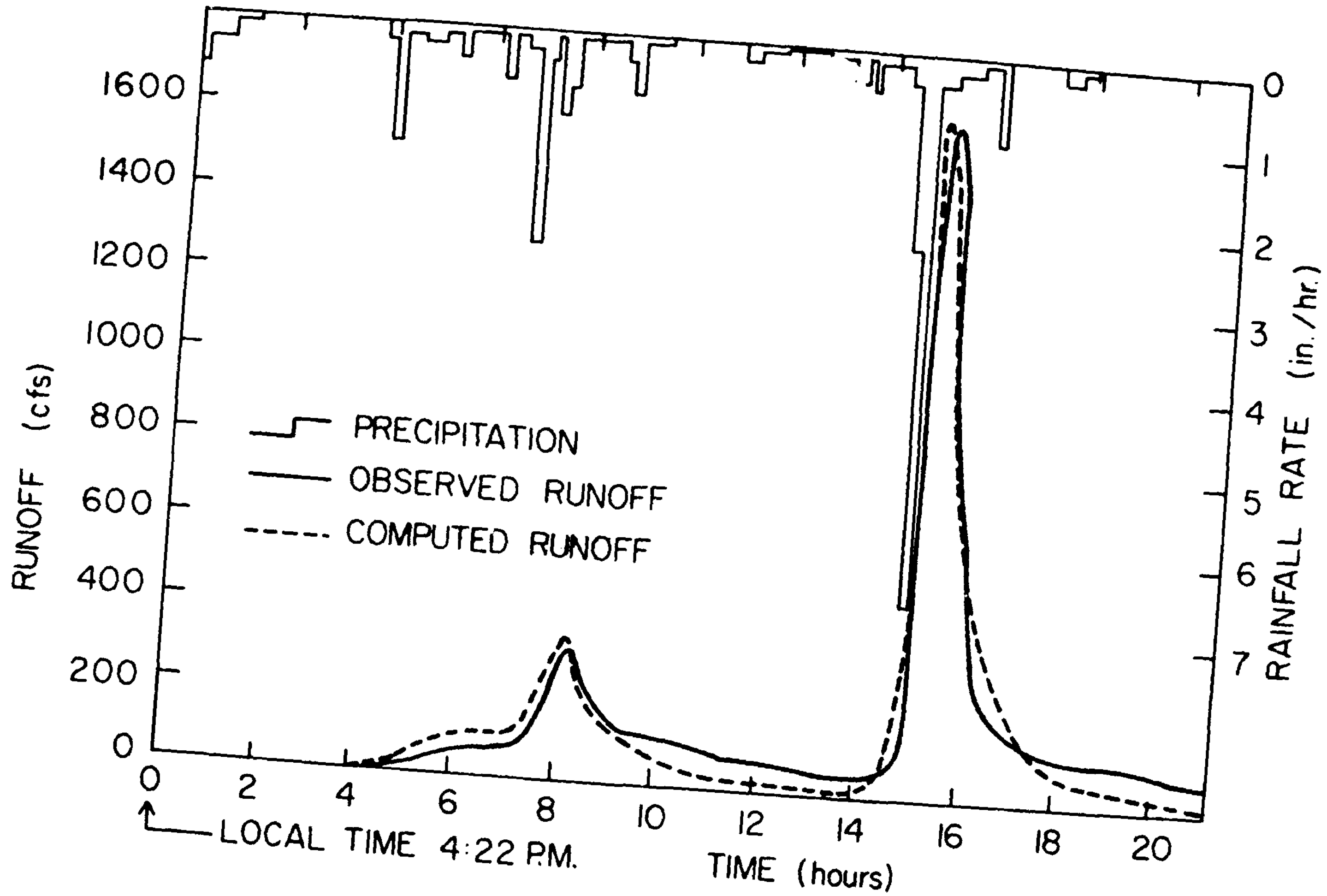


Figure 37 Runoff Hydrograph from Watershed W-5 for the February 21, 1971 Calibration Event

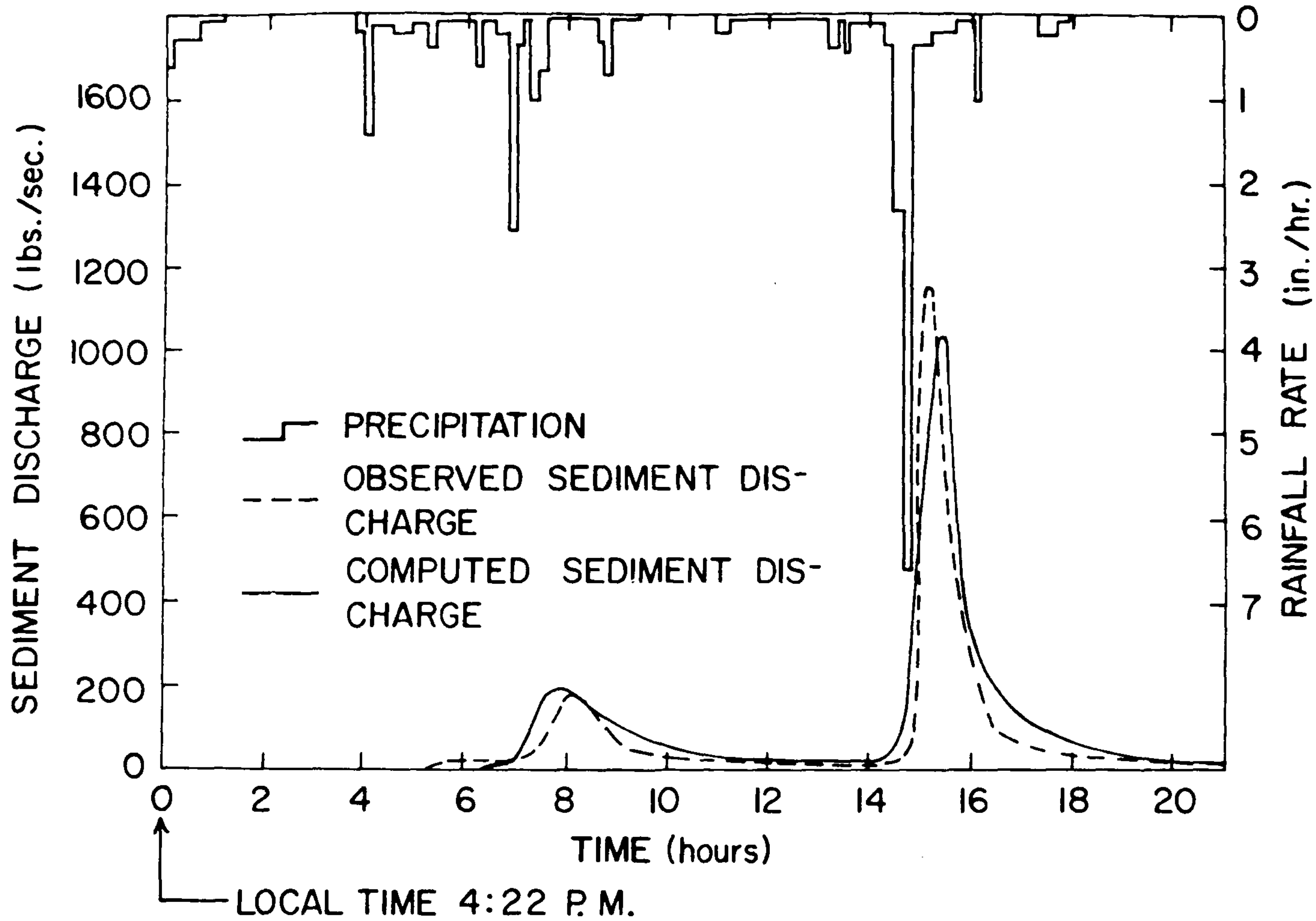


Figure 38 Sedimentgraph from Watershed R-5 for the February 21, 1971 Calibration Event

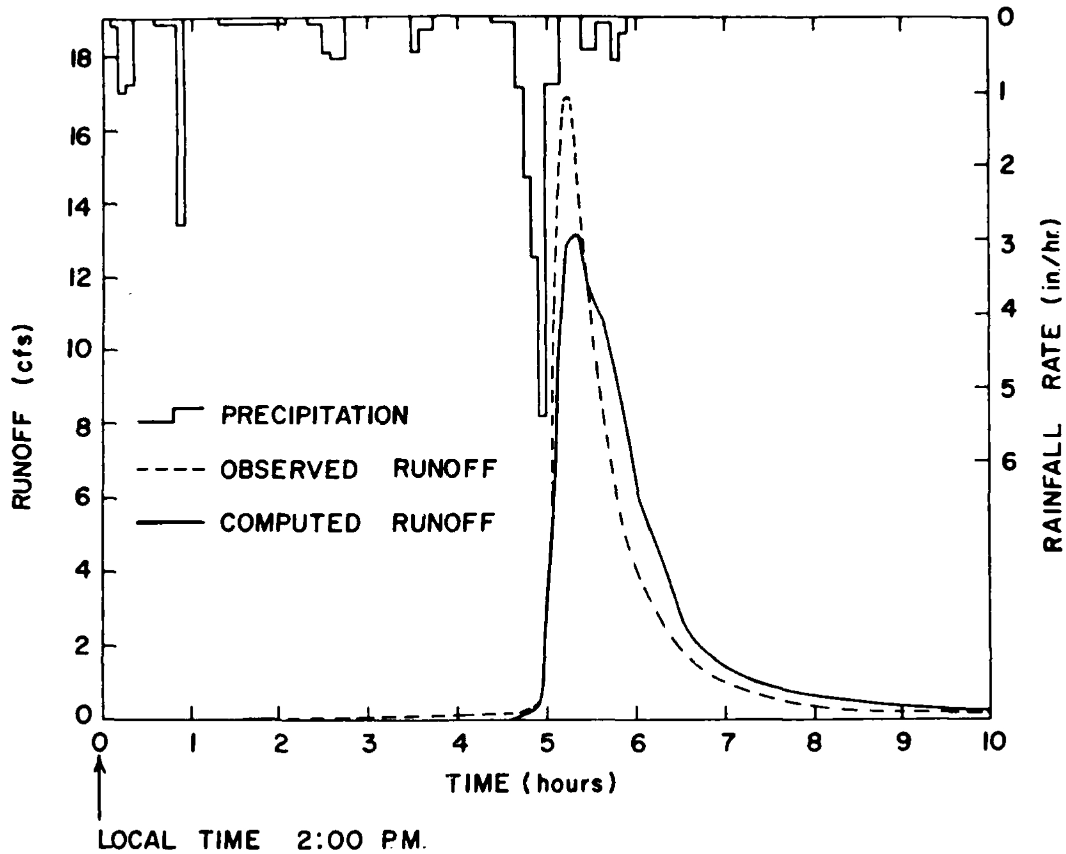


Figure 39 Runoff Hydrograph from Watershed R-5 for the May 6, 1969 Calibration Event

AD-A101 385 SOIL CONSERVATION SERVICE OXFORD MS SEDIMENTATION LAB F/G 8/8
STREAM CHANNEL STABILITY.(U)
APR 81 D G DECOURSEY

UNCLASSIFIED NL

3 OF 3
AD
A101385

END
DATE
FILMED
8-81
DTIC

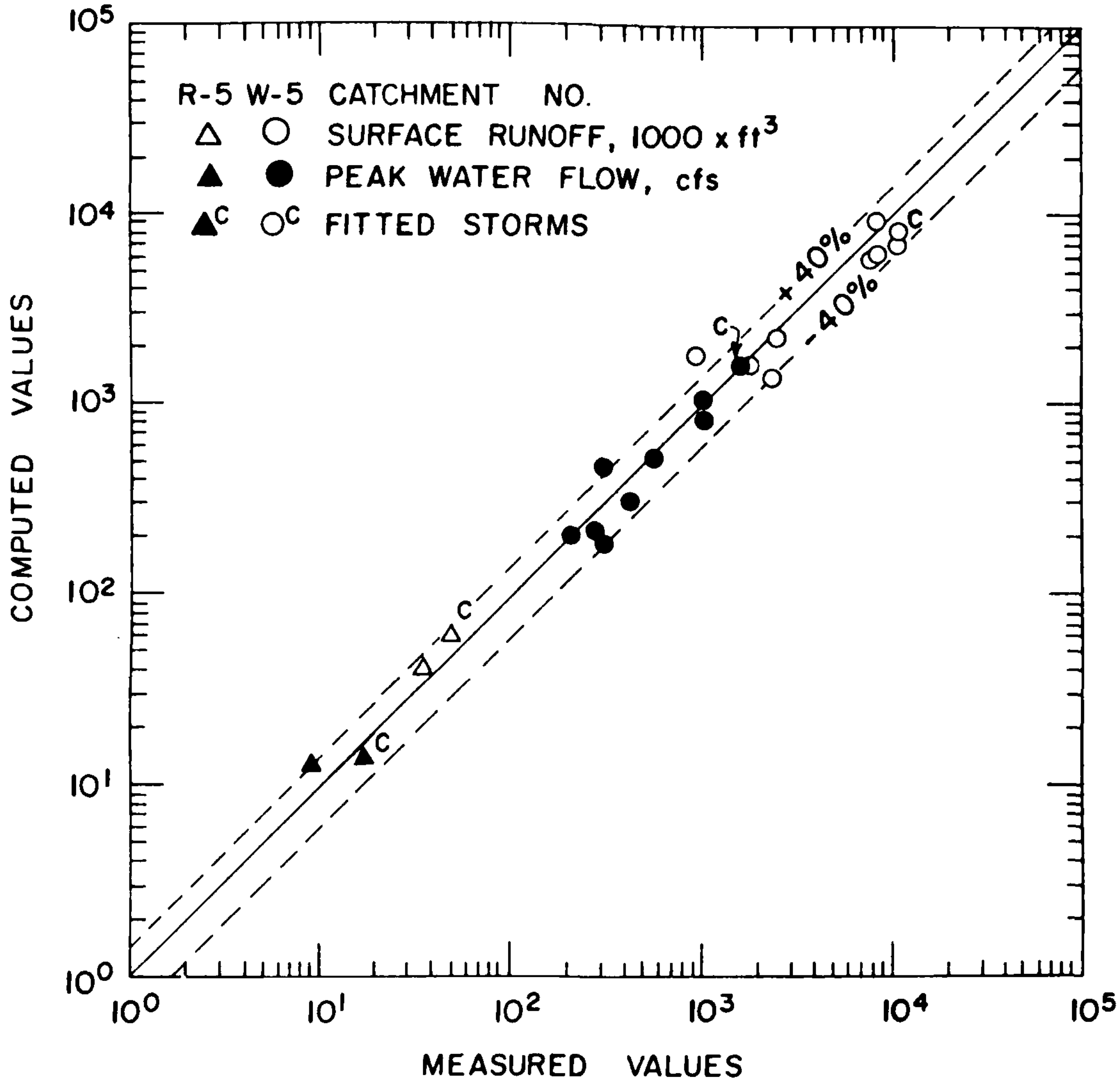


Figure 40 Comparison of Measured and Computed Water Yields and Peaks

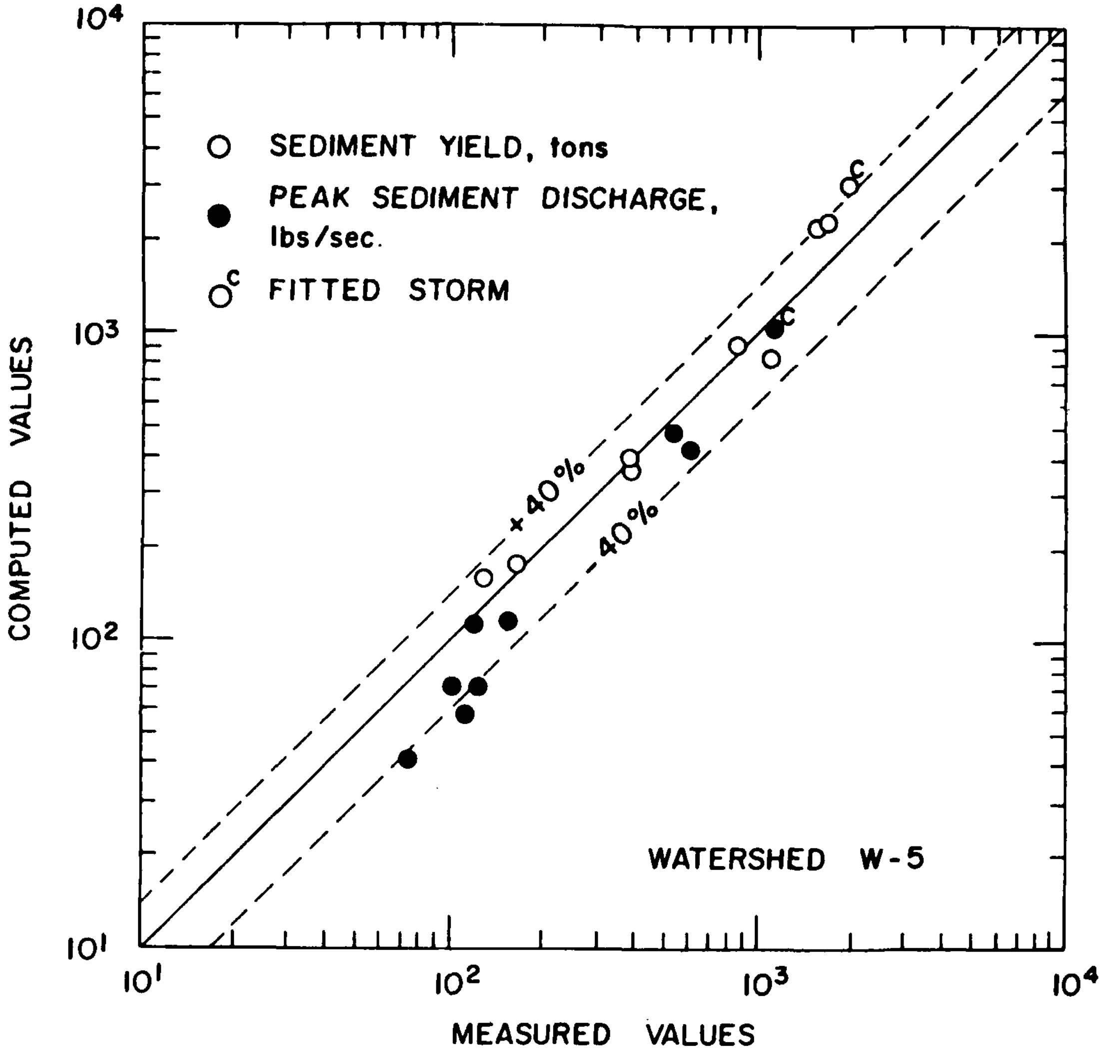


Figure 41 Comparison of Measured and Computed Sediment Yields and Peaks

8.5.2 Two-Dimensional Hydraulic Model

Testing of the two-dimensional model has been quite limited. In particular, the tests have been restricted to the movement of cohesionless materials under laboratory conditions. No field data, with sufficient detail and accuracy, have been found for testing the ability of this scheme to simulate natural processes. Further testing of the method is clearly needed. In one application, the natural backfilling of a trench dredged across an alluvial bed was simulated. The simulation was verified by reconstituting data collected by Kerssens et al. (1977). In this experiment a trench was formed in a sand bed in a laboratory flume. The downstream slope of the trench was small enough to ensure that no flow separation would occur. Water and sediment were supplied at constant rates indicated in Figure 40. Most of the bed load was carried in suspension. The bed profile was measured after seven and fourteen hours of continuous flow. These profiles are shown in the upper part of Figure 42 along with the simulated free-surface and bed elevations. The comparison between the observed and measured bed profiles is satisfactory. The water surface profiles correctly reproduce the surface rise over the trench. As the trench is silted up the water crest diminishes and moves downstream with the trench as expected. Figure 43 depicts the distribution of suspended sediment through the flow domain after seven hours. The contours of constant concentration were drawn from computed results. Sediment deposition occurs on the upstream side of the trench as the stream decelerates and loses carrying capacity. As the flow regains velocity, sediment is entrained along the downstream side and dispersed upwards. The suspended material leaving the trench area gradually approaches a new equilibrium distribution.

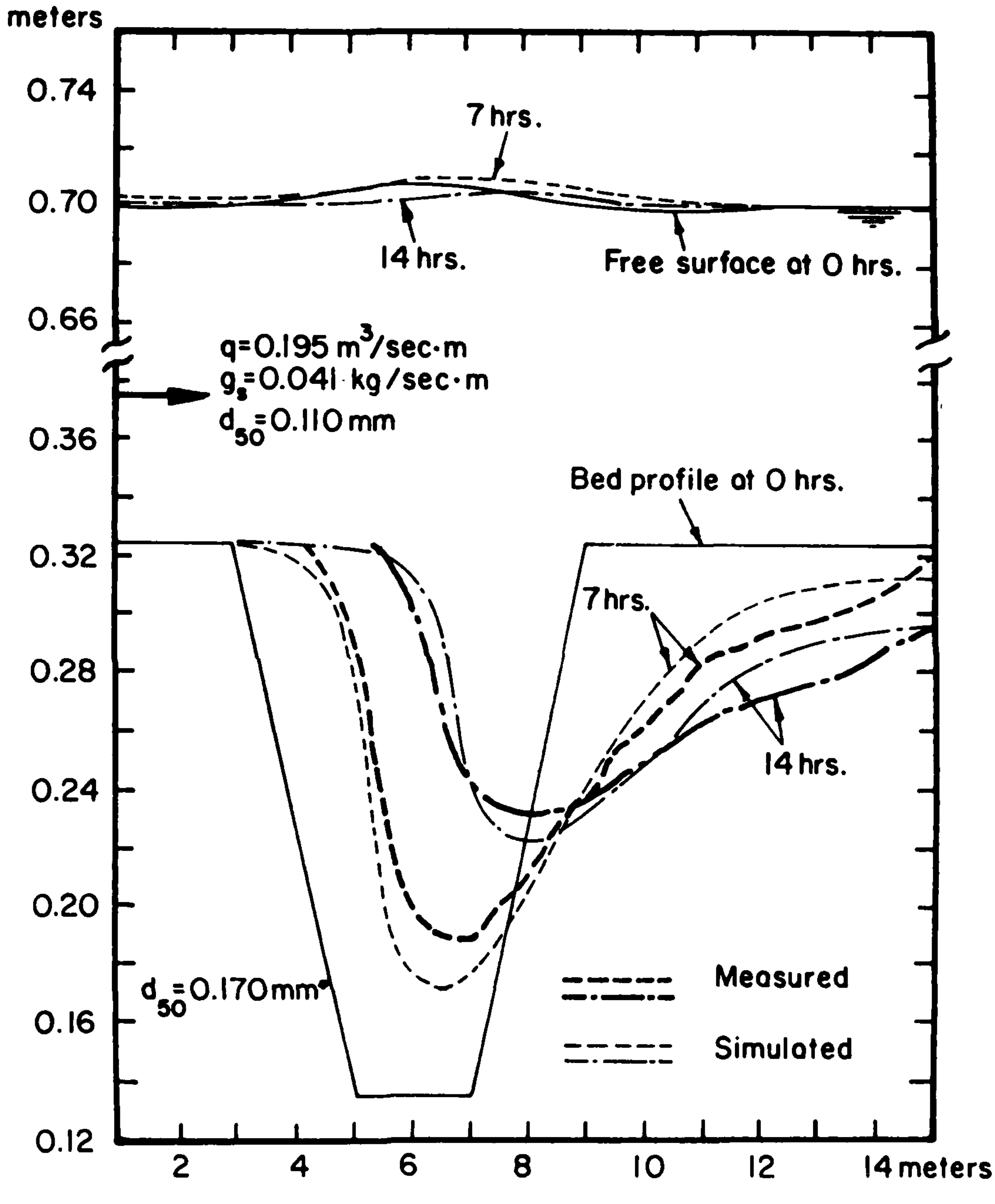


Figure 42 Comparison of computed and observed water surface and bed profiles of flow across a trench

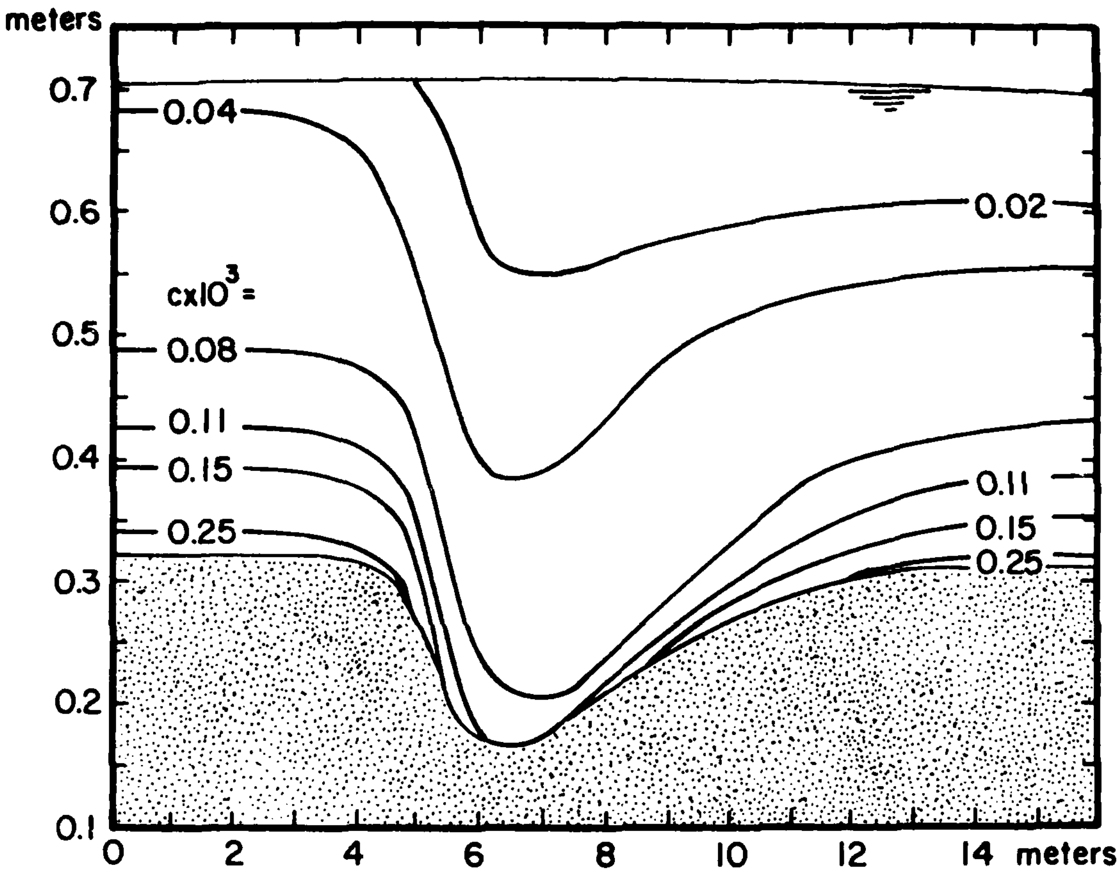


Figure 43 Computed sediment concentrations of flow across a trench

9 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This Comprehensive Report on Channel Stability was written to describe how to analyze a channel stability problem. Therefore it is rather general; only the last chapters describe problems of channel stability in the Yazoo River Basin. Detailed reports of the various research projects associated with our study of channel stability problems in the Yazoo River Basin are presented as Appendices. These Appendices address all five project objectives of the agreement between the Vicksburg District, US Army Corps of Engineers, and the Sedimentation Laboratory. Table 8 is a summary of the objectives and the projects that relate to them. The following material summarizes the material presented in the first eight chapters of this report. The conclusions and recommendations include summaries of material presented in the Appendices and is presented by project objective.

9.1 SUMMARY

The Yazoo River Basin in Mississippi has been a source of problems for many decades, with excessive erosion and bank instability necessitating costly countermeasures both in the hill region and in the downstream Delta area. Hill streams are degrading, resulting in bank caving land loss, and damage to highway bridges. Many streams have enlarged to the extent that 50 to 100-year runoff events are contained within banks. Downstream aggradation is caused by the lower channel slopes that exist in the Delta. It results in more frequent flooding and loss of navigation. The demonstration project, Work Unit 7, is directed toward determining the causes of stream channel instability in the Yazoo Basin, whether chronic or acute, and toward developing ways to work best with natural controls to develop the least expensive program to re-establish drainage basin stability. A wide variety of bed and bank stability measures are being tested to determine the most economical and effective means of providing the needed protection.

The research program; conducted under Reimbursable Agreement with the Vicksburg District, Corps of Engineers, at the USDA Sedimentation Laboratory; was initiated to gain better knowledge of channel stability problems and of improved methods for channel stabilization. The need for this program is emphasized by the extremely complex combination of events, site conditions and land-use changes that have been responsible for channel stability problems that exist in the Yazoo River Basin. The complexity of

Table 8 Research Objectives and Research Projects

Research Objective 1.

Determine the infuence of grade control structures on channel stability.

Research Project:

1. Model Study of the Low Drop Grade Control Structures (Appendix B) by W. C. Little and J. B. Murphey

Research Objective 2.

Monitor the performance of selected channel stabilization methods.

Research Projects:

1. Evaluation of Streambank Erosion Control and Demonstration Projects in the Bluffline Streams of Northwest Mississippi (Appendix A) by W. C. Little and J. B. Murphey
2. Investigations of Vegetation for Stabilizing Eroding Stream Banks (Appendix C) by A. J. Bowie

Research Objective 3.

Evaluate the effects of geology, geomorphology, soils, land use, and climate on runoff and sediment production from major source areas.

Research Projects:

1. Goodwin Creek: Catchment, Data Collection and Data Management (Appendix F) by E. H. Seely, E. H. Grissinger and W. C. Little
2. Soil Erosion and Sediment Characteristics of Typical Soils and Land Uses in the Goodwin Creek Catchment (Appendix G) by L. D. Meyer and W. C. Harmon
3. Hydrologic Measurements on Typical Soils in the Goodwin Creek Catchment (Appendix H) by M. J. M. Römkens

Research Objective 4.

Estimate the water and sediment production from a large mixed land use watershed and the integrated effects on channel stability.

Research Projects:

1. Single Event Numerical Model for Routing Water and Sediment on Small Catchments (Appendix I) by D. K. Borah, C. V. Alonso and S. N. Prasad

2. Numerical Model for Routing Graded Sediments in Alluvial Channels (Appendix J) by C. V. Alonso, D. K. Borah and S. N. Prasad
3. Two-Dimensional Finite-Element Model for Routing Water and Sediment in Short Alluvial Channel Reaches (Appendix K) by T. Y. Su and S. Y. Wang
4. Stochastic Properties of Turbulent Tractive Forces in Prismatic Channels (Appendix L) by C. V. Alonso and N. L. Coleman
5. Large Scale Model Study of Bed Material Transport (Appendix M) by J. C. Willis
6. Alluvial Channel Flow Resistance: Stochastic Properties (Appendix N) by N. L. Coleman and R. B. Wilson

Research Objective 5

Evaluate the relation between valley stratigraphy and channel morphology and their combined effects on channel stability.

Research Projects:

1. Bank Stability and Bank Material Properties in the Bluffline Streams of Northwest Mississippi (Appendix D) by C. R. Thorne, J. B. Murphey, and W. C. Little
2. Geomorphic Controls of Channel Stability (Appendix E) by E. H. Grissinger and J. B. Murphey

the processes functioning in the basin and the significant influence that the condition of the watershed upstream has on channel stability, indicates that the most feasible approach to the solution of channel stability problems would combine upland conservation management practices with channel stability design on a watershed basis. This approach has the added benefit that it would maintain or enhance crop productivity of the upland areas.

The Laboratory's research program encompasses studies of both watershed management practices and channel protection activities. Channel stabilization devices have been constructed on bluff-line tributaries of the Yazoo River for observation. The Goodwin Creek Watershed was instrumented to evaluate the influence of upstream watershed conditions on channel stability. The field studies were supported by laboratory studies of flow resistance, turbulence and sediment transport. Several hydrologic models were developed to aid in interpretation of data and assessment of remedial activities.

The research program had five major objectives:

1. Determining the influence of grade control structures on channel stability.
2. Monitoring the performance of selected channel stabilization methods.
3. Evaluating the effects of geology, geomorphology, soils, land use, and climate on runoff and sediment production from major source areas.
4. Estimating the water and sediment production from a large, mixed-land-use watershed and the integrated effects on channel stability.
5. Evaluating the relation between valley stratigraphy and channel morphology and their combined effects on channel stability.

These five research objectives were addressed in several overlapping projects. Reports of these projects are presented in the Appendices to this report. This comprehensive report on the study of channel stability problems in the Yazoo Basin is presented to demonstrate an approach used in making as assessment of channel stability.

Chapters 2 thru 7 are materials that provide the reader with general information of the type needed to make assessments of channel stability.

Chapter 8 is a description of Goodwin Creek and an assessment of channel stability in Goodwin Creek watershed. The material presented in the chapters is as follows:

Chapter 2, River Characteristics and Morphology, provides a summary of major topics in channel morphology. The transport processes responsible for the movement of channel bed material and the bed forms that characterize alluvial channels in both the upper and lower flow regimes are described. Channel roughness, composed of grain, bed form and plan form elements is described as a dynamic system. The turbulence forces responsible for entrainment of sediment particles are described. Physical characteristics of material that normally make up the bed and banks of stream systems are also described. Areas of excessive erosion and deposition in bendways are discussed. The characteristics of straight, sinuous, meandering, or braided alluvial channels and how they relate to sediment transport rates, channel slope, and discharge are described. The last section of the chapter describes various geomorphic relations of channel size, shape, and sinuosity.

Chapter 3, which pertains to the impact of watershed processes on the channel system, describes the effect of land use management practices in the upland watershed on volumes of runoff and sediment production. Sources of sediment production and man's influence on these sources of sediment are discussed. Changes in the climate of a region as they influence runoff and sediment yield are also discussed.

Chapter 4 describes processes leading to channel instability and erosion. Included are discussions of fluvial entrainment of bed and bank materials, particle segregation and armoring, the erosion of cohesive materials, weathering of surface materials, processes responsible for sloughing and massive bank failure, liquefaction of silty and sandy soil, and erosion of bank materials caused by seepage and wave action. The latter part of the chapter describes geomorphic processes or mechanisms of channel erosion. These processes include changes in flow rate, sediment load, and channel slope. The effect that these changes have on channel stability are described.

Chapter 5 discusses the many methods of channel protection with emphasis on the use of grade control and vegetation as the two most cost-effective measures. Also described are armor, retards, dikes or jetties, bulkheads, and baffles.

Chapter 6 identifies the processes active in a given situation and evaluates effectiveness of specific problem solutions. It was written to aid individuals in solution of specific site problems. The concepts of channel system instability, channel reach instability, and channel cross-section or point instability, are discussed in depth. An approach to such a study describes the necessary material to be collected, sources of useable data, and use of mathematical models or other procedures for use in assessment. Four major causes of channel system instability (land use change, climatic change, downstream control, and excedence of a threshold of stability) are described using historic information, the application of geomorphic relations, and hydrologic models. Alternatives to solution of stability problems include "living with the existing channel system" if its equilibrium size has already been reached and use of grade control in conjunction with upland watershed treatment measures. Channel reach and channel point instability are discussed in less detail.

Chapter 7 is a brief discussion of some of the mathematical models that have been developed or are under development for possible use in studying channel stability. The first part of the Chapter describes how some of these models are applied to streambank stability problems. The stability of non-cohesive, cohesive and composite banks are discussed. The effect of tensile cracks, which are prevalent in many high, steep banks is included in the discussion. Three hydrologic-type models are described. They are a single event model, a continuous simulation model, and a quasi 3-dimensional finite element model. The single event model is physically-based and was developed because the bulk of the sediment moves during a few large storm events. Interception, infiltration, overland and channel water routing, overland sediment routing, channel sediment routing and input data requirements are discussed. The proposed continuous simulation model is easier to use and requires less input data. Routing of water and sediment from the model is accomplished using the channel component of the single event model. Procedures used to estimate the volume of surface runoff, percolation, return flow, evapotranspiration, water balance in reservoirs, sediment yield and input data requirements are discussed. The quasi 3-dimensional finite element model discussed was developed to analyze sediment movement at specific sites in a stream channel; for example, at the confluence of two channels or in the vicinity of various stabilization

structures such as those presented in Chapter 5. This model is not yet operational, but the potential for its full development is good enough that the concepts are presented.

Chapter 8 is an assessment of channel stability problems in Goodwin and Johnson Creek Watersheds and a description of the research facilities placed in operation in the Goodwin Creek Watershed. The Chapter includes a description of the watersheds, including criteria for their selection as a research facility.

Chapter 9 contains the Summary, Conclusions, and Recommendations. The Summary is nearly the same as this Executive Summary. The Conclusions and Recommendations are presented in the order of the five Research Program Objectives. The summarized material is presented in detail in the 14 Appendices. To avoid presenting a confusing picture, the recommendations immediately follow the conclusions for each of the five objectives. Only in the discussion of Research Objective 4 is the above pattern not followed. Since Objective 4 is primarily the development of mathematical models that can be used to estimate runoff and sediment yield, it consists of rather independent sets of material. In this case, the recommendations follow the conclusions for each project.

This Comprehensive Report on Channel Stability was written to describe how to carry out an analysis of a channel stability problem. Therefore it is rather general; only the last chapters describe problems of channel stability in the Yazoo River Basin. Detailed reports of the various research projects associated with our study of channel stability problems in the Yazoo River Basin are presented as Appendices. They are completely independent reports and need no introductory material. In total they address all five project objectives included in the Reimbursable Agreement between the Vicksburg District of the US Army Corps of Engineers and the USDA Sedimentation Laboratory.

9.2 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are presented for each of the five Research Project Objectives. These conclusions and recommendations summarize material discussed extensively in the Appendices.

9.2.1 Research Objective 1

Determine the influence of grade control structures on channel stability.

9.2.1.1 Conclusions: Hydraulic model tests of low drop structures led to the following conclusions:

1. A low drop structure can be defined as one in which the amount of physical drop in the structure is less than or equal to the critical depth, y_c, of the design discharge.

2. General design criteria are tentatively based on the channel bottom width and critical depth of the design discharge.

9.2.1.2 Recommendations:

1. Results obtained from the model studies completed thus far indicate that the remainder of the originally planned tests should be completed before finalizing design criteria for the structures.

2. Field observation of a variety of structures should be continued to determine the cost-effectiveness and influence on the channels up and downstream.

9.2.2 Research Objective 2

Monitor the performance of selected channel stabilization methods.

9.2.2.1 Conclusions: Observations of channels and protective measures throughout the bluffline channels of the Yazoo Basin led to the following conclusions:

1. Causes of stream channel erosion can be traced to:

a. Channel straightening that leads to increased slope, increased carrying capacity, increased volumes and peaks of within bank flows, higher velocities, incision into infertile materials that will not support vegetative growth, incision into extremely erodible materials and elimination of vegetation that reduces high velocities, thus increasing susceptibility to bank erosion.

b. Dredging of main channels that increase the slope of tributaries and thus their flow velocity and sediment transport capacity. This leads to a new wave of tributary degradation as overfalls develop and migrate upstream leaving the channels deeper and with steep banks susceptible to gravity failure.

c. Regulated flows from major reservoirs reduce the water levels in downstream channels during flood periods. Tributaries which would normally have backwater effects from high water in the major channels have increased hydraulic gradients due to the lower water levels. This leads to higher velocities and problems described in b above.

d. Characteristics of the channel bank and bed materials influence the stability of the channels. The young paleosols are unconsolidated silt and sand and fail by massive gravity induced slumping along tension cracks. Old paleosols are highly consolidated fine materials that fail in blocks, as sands and other materials are winnowed from their well developed polygonal structure. As long as the channel bed remains in the old paleosol, the channel is relatively stable. However, if knickpoints or other processes cut through the paleosol, underlying unconsolidated sands and gravels lead to rapid failure of the banks as undercut banks fail. Channel irregularities such as seepage zones, cattle crossings, overbank drainage, buried channels, organic deposits, sand bars, dispersive soils, broken rock sills, toppled trees, trash or bridge piers and culvert misalignment can direct flow to vulnerable banks leading to point instability. If not properly handled, these point instabilities can enlarge to reach and system instability.

2. The effectiveness of channel protection measures has been tentatively evaluated:

a. Low drop grade control structures have been found to be economical and effective for stabilizing channels where knickpoints or excessive channel slopes are encountered.

b. Ten combinations of structural and vegetative bank revetments on Johnson Creek failed partially because the channel degraded about four feet. Thus, bed control is essential to success of such treatment and should be installed first.

c. Establishment and maintenance of vegetative protection requires slopes less than 1 on 2.

d. Under ideal conditions at least two or three growing seasons are required to establish vegetative cover. Woody species that

are expected to provide better protection to lower banks will require more than five years to establish.

e. Preliminary assessment of the survival rate of several varieties of grass, vetch, shrubs and trees shows selected species to be better than others and survival to be site specific.

9.2.2.2 Recommendations: Many years are required to evaluate the effectiveness of both structural and vegetative protection measures. It is recommended that field observations of both be continued for several years to observe their response to a variety of hydrologic events.

9.2.3 Research Objective 3

Evaluate the effects of geology, geomorphology, soils, land use and climate on runoff and sediment production from major source area.

Response to this objective requires hydrologic data. As a result of a variety of circumstances, data collection from the Goodwin Creek Watershed has been delayed. However, as of the date of this report, eight runoff measuring stations and the climatic data station are fully operational. Peripheral data on land use, pond water elevations, etc., are also being collected. Rainfall and runoff records are available from stations that are not on the telemetry system.

9.2.3.1 Conclusions:

1. A research watershed has been established and instrumented on Goodwin Creek, a small Bluff-line tributary to Peters Creek in Panola County, MS. This watershed has a range of sediment source areas and channel types; land use is approximately evenly-divided between cultivated land, woodland, and pasture. Measurements are being made on sediment transport, discharge, soil types, geology, land use, soil moisture, temperature, rainfall and other climatological variables. These data are being processed and stored in a data base to support additional research.

2. Results of field tests on the erosion and sediment characteristics of soils in the Goodwin Creek area show that the soils are among the most erodible found anywhere in Mississippi. Erosion from cultivated fields is extremely high; however, interrill erosion rates from good pasture and woodland are relatively insignificant. The sediment eroded from these soils is highly-transportable and, because the soil

particles are so small, it is difficult to trap. Since the slopes of the channels transporting the sediment determine to a great extent the amount transported, every effort must be made to orient the rows to minimize the slope. This is extremely difficult in the steep hills found in this area.

3. Based on field tests, soils in the watersheds show internal drainage characteristics ranging from moderate in the bottom land soils to extremely slow in the upland soils. Impact of the soils on channel stability will come primarily from sustained low flows as a result of deep seepage and surface runoff when rainfall intensity exceeds the infiltration rate. Slow internal drainage is created by the presence of fragipans or relatively impermeable soil layers. The lack of vertical water movement in the soil profile leads to rapid filling of the storage capacity, runoff takes place quickly, and surface flow concentrates as specific locations on the upland slopes. This leads to rilling and gully formation. Lateral movement of water above the tight soil layers may lead to seepage at various points in the channel walls, causing possible bank failure.

9.2.3.2 Recommendations:

1. Instrumentation of the research watersheds should continue as rapidly as possible so that complete data sets can be obtained.

2. Work on the data management and retrieval system should be completed as soon as possible.

3. Investigations of rill erosion for major soils and land use conditions should be pursued to complement the interrill erosion data.

4. A study of sediment transport along row furrows should be initiated.

5. The sizes of sediment coming from rill erosion in these soils should be evaluated and its transport potential should be determined.

6. The effect of various tillage practices and land uses on surface sealing phenomena of the soils found in the Goodwin Creek Watershed should be determined.

9.2.4 <u>Research Objective 4</u>

Estimate the water and sediment production from a large mixed land use watershed and their integrated effects on channel stability.

Research projects directed toward meeting this objective were primarily the development of mathematical hydrologic models and flume studies of channel resistance and sediment transport.

9.2.4.1 Single Event Watershed Model

9.2.4.1.1 Conclusions:

1. A numerical model for routing water and sediment on small watersheds has been developed.

2. The model can simulate the effects of different land uses on agricultural watershed from a few acres to about 5 square miles by changing only the input data.

3. The model is based on the physical processes governing the mechanics of water and sediment movement and requires calibration of four parameters.

4. The model predicts the surface component only. It does not predict the subsurface and groundwater movement.

5. The model is restricted to streams where the channel geometry changes little during a storm event, and in which the kinematic-wave approximation for flow routing is valid.

6. The model simulates single storm events, the user must estimate the initial conditions for the storm. However, it can be applied to a sequence of rainfall events if the user can make satisfactory estimates of the initial soil moisture conditions.

7. The model has been validated with data from the Pigeon Roost Creek Watershed, W-5, in Northern Mississippi, and the Watershed, R-5, near Chickasha, OK. The shape of water and sediment hydrographs, and total water and sediment yields of a number of events were satisfactorily simulated.

9.2.4.1.2 Recommendations:

1. It is recommended that the model be tested for additional data. Its evaluation and continuous updating are essential to its credibility and effectiveness.

2. It is recommended that the model be further developed or modified to permit continuous simulation over long time spans (about 50 years). This is essential in evaluating the long-term response of a watershed or stream network, which is dependent not only on the history of management practices, but also on the sequence of storm events.

3. It is recommended that the model be further developed to track the channel geometry of streams that become ustable due to bank erosion and deposition.

4. It is recommended that data-gathering efforts be continued to provide an adequate data base for further model development and validation.

9.2.4.2 Routing Water and Sediment in Alluvial Channels

9.2.4.2.1 Conclusions:

1. A one-dimensional numerical model has been developed for simulating the movement of well graded sediment mixtures through a stream network.

2. Hydraulic routing is performed by using any acceptable algorithm supplied by the user because the water movement is assumed to be uncoupled from the sediment transport process. The model can be used in tandem with any suitable sediment yield model that supplied the water runoff and sediment from lateral areas.

3. Sediment routing is based on the physical processes governing the mechanics of sediment movement in alluvial channels. The model recognizes the effect of bed load-suspended load interaction on the total load movement, and it can simulate bed armoring, changes in bed elevation, and longitudinal sorting of eroded materials.

4. The model is restricted in application to noncohesive materials, relatively stable channel geometries, streams with negligible transport in-to and out-of the banks, and flows in which transverse currents may be ignored.

5. The channel model gave satisfactory results when tested on laboratory data from a flume armoring study, and field data from the San Luis Valley Canal, Colorado, and the East Fork River, Wyoming. These tests tend to indicate that the model adequately simulates the transport of graded cohesionless sediments, including the effect of armoring.

9.2.4.2.2 Recommendations:

1. The channel model should be further tested in a variety of situations with emphasis on the scour, deposition, and transport of noncohesive materials.

2. The model should be further developed to include the following capabilities:

a. improve one-dimensional representation by separating flows in the incised channel from flows over flood plains;

b. account for in- and out-of-bank transport, and a transverse distribution of bed-material properties and hydraulic conditions;

c. predict transverse bed slope and selective deposition in channel bends; and

d. simulate the sediment deposition in grasses and other vegetative material along stream channels.

3. The channel model should be tested using hypothetical situations to confirm that the model responds in a realistic manner. Those tests should include the following channel-stability related applications:

a. Combine the channel model with the continuous sediment yield and bank-stability models. Run the combined models for a period of a few years, and predict the size and grade of channel needed to maintain a bank height-slope that is stable for a given stratigraphic condition.

b. Run the combined models for a combination of channel depths and slopes and observe what combination of bed armoring and/or grade control structures are needed to stabilize the channel.

c. Select a range of storm events and use the combined models to study slough of bank material and define channel width and/or armoring coat that is needed to prevent erosion of slough material.

4. It is recommended that detailed sediment transport data be collected from the Goodwin Creek Watershed to provide an adequate base for further model development and validation.

9.2.4.3 Two-dimensional Model

9.2.4.3.1 Conclusions:

1. A two-dimensional model has been developed to predict water and sediment movement and bed-elevation changes in channel reaches with irregular geometry.

2. The model is based on conservation of mass of both water and sediment, and momentum equations. These equations of motions are solved using a finite-element scheme.

3. The model has been validated by simulating laboratory data obtained from a trench scour-and-fill study. The model predicts the evolution of the water and bed surface elevations. In another test, the model was used to simulate bed scour around a spur dike. The shape of the predicted scour hole is in qualitative agreement with observations reported in the literature. However, the deviations observed in the predicted locations of maximum scour and deposition identify limitations in the model when simulating situations dominated by regions of flow separation. Further research is needed to correct the deficiency.

9.2.4.3.2 Recommendations:

1. The model should be further developed and tested on more complete data sets to ensure its accuracy and credibility. Work should continue on the computer code to improve its flexibility and efficiency. Carefully designed laboratory experiments should be conducted to investigate the accuracy and range of applicability of transport algorithms used in the model (i.e., turbulence closure schemes, two-dimensional sediment transport functions, etc.).

2. Verification and validation of two-dimensional models require data with a degree of detail and spatial resolution that is practically nonexistent. Thus, it is recommended that laboratory data be collected in scaled-down physical models reproducing conditions observed in the field. Laboratory studies can provide, at a reasonable cost, velocity, sediment transport and cross sectional data with the high degree of resolution needed in model validation. Then fewer carefully selected prototype measurements in the field will suffice for model verification.

3. Hypothetical situations should be used to confirm that the model responds in a realistic manner. To this effect, the two-dimensional model can be linked to a channel and a sediment yield model to investigate the dynamic response of bendways, point bars, and stabilization structures such as spur dikes, to changes in upstream land management practices, and to a series of intense storm events.

9.2.4.4 Study of Turbulent Tractive Forces

9.2.4.4.1 Conclusions: This report presents recent measurements of the statistics of the instantaneous boundary shear stresses in a smooth-wall

open channel flow. These measurements were made along the wetted perimeter of a channel flow with an aspect ratio of about 4.4 and a Reynolds number of about 1.7×10^5. The results reveal the following information:

1. Measurements of shear stress fluctuations along the wall and bed of the flume suggests that the mean secondary flow affects the cross-sectional distribution of relative intensity of boundary shear.
2. The distribution of boundary shear stress have instantaneous standardized values ranging from -2.5 to 10.00 along the bed and from 2.5 to 7.7 along the wall. The shape of the distribution of shear stress values suggest that large-scale eddies are responsible and these could have significant impact on sediment transport.

9.2.4.4.2 Recommendations: The studies reported above were confined to turbulent flows over hydraulically smooth beds, using sensing devices suitable only for laboratory practice. There is a need to (i) extend these types of measurements to fully rough bed conditions, usually encountered in the field, and (ii) develop tractive-force measuring techniques appropriate for the field environment. The following experimental program is recommended:

1. Adapt a commercially-available force transducer to measure instantaneous unit tractive-forces acting on discrete roughness elements. This will permit direct measurement of the turbulent tractive forces acting on boundaries ranging from smooth to fully rough.
2. Use hot-film anemometry techniques to measure the turbulent flow characteristics in the proximity of the channel bed.
3. Investigate the relationship between the bed tractive forces and the turbulent velocity field. This should be done over the entire range of bed roughnesses and for a wide variety of flow Reynolds numbers and aspect ratios. This information will permit the estimation of the tractive-force distributions from direct measurements of the velocity field in the proximity of the bed.

9.2.4.5 Large scale study of bed material transport

9.2.4.5.1 Conclusions: The following conclusions are tentative because not all tests are complete and analyses are still incomplete. Results of the flume studies indicate that mean sediment concentrations of large scale studies are significantly larger than expected, relative to results from

small scale tests; however, the bed surfaces were geometrically similar. The data indicate a single relationship between energy gradient or friction factor and Froude number. The Froude number is the primary dependent similitude number for sediment transport and flow in alluvial channels.

9.2.4.5.2 Recommendations: Detailed statistical analyses should be completed. Additional experiments should be carried out to extend the time span of the temporal records for a better estimate of the mean concentration, temporal standard deviation of the bed surface, and the temporal spectral moments.

9.2.4.6 Stochastic Properties of Alluvial Channel Flow

9.2.4.6.1 Conclusions:

1. A total of 112 experiments were completed in this study without stoppages due to instrument failure. Of these experiments, 39 displayed simultaneous stationary records of the resistance coefficient and of the sand bed elevation, from which the time-mean form roughness was calculated.

2. Although data scatter was large, tentative time-mean-resistance functions were defined for the subcritical and supercritical flow regimes. These functions were of the Nikuradse form, in which an expression for relative roughness was the independent variable.

3. The standard deviation of a record of bed elevation against time was found to be a useable expression of bedform roughness if it was divided by a time constant.

4. Individual time records suggest a relation between the time mean bed form roughness and the resistance coefficient. If this relation exists, its form will depend on the Froude number.

5. No evidence of coupling could be found between time constants of the resistance coefficient and the propagation of bedforms down the study reach.

6. The temporal variation of the resistance coefficient was not related to the relative roughness of the study reach in a given flow.

9.2.4.6.2 Recommendations:

1. Improvements in instrumentation are needed so that longer periods of record can be achieved without instrument stoppages. The nature of a sand bed elevation record indicates that a higher proportion of stationary records of resistance coefficient and of sand bed elevation

would have been obtained if the records had been longer. This would lead to better values of the bed form roughness, and hence better correlation in the resistance functions.

2. Studies of transient mean velocity at constant flow depths should be carried out to observe changes in the bed.

3. Similar experiments with transient depth at constant mean velocity should be completed and changes in bed observed.

4. After these experiments, analyses of the data should be carried out to see if it is possible to separate the effects of mean velocity and flow depth that are coupled in a normal hydrograph of flow.

5. Experiments including preprogrammed hydrographs of simultaneous variations of depth and mean velocity should be initiated to formulate the mathematical model for variation in the friction factor indicated by the previous experiments and analyses.

9.2.5 Research Objective 5

Evaluate the relation between valley stratigraphy and channel morphology and their combined effects on channel stability.

9.2.5.1 Conclusions:

1. Channel stability and instability on Johnson and Goodwin Creeks has evolved from site specific conditions, stratigraphic controls, and system characteristics. Bank instability in Johnson Creek is prevalent downstream of major knickpoints, whereas the banks upstream of the knickpoints are relatively stable. The knickpoint has progressed upstream at an average rate of about 600 feet per year for the last 40 years. It has eroded through the cohesive old paleosol materials present as bed material upstream of the headcut and sufficiently lowered bed elevation to accentuate gravity-induced failure of bank materials. Reaches downstream of the headcut have beds of sand or gravel. Goodwin Creek, on the other hand, has not undergone thalweg lowering, due to the presence of iron-cemented sandstone outcrops in the channel bed, which function as temporary bed-control sills, and to the large amount of gravel bed material that is present. Lateral movement of the channel has occurred to varying degrees throughout Goodwin Creek.

2. Gravity-induced failure is the most frequent form of bank instability. Failure of young paleosol and postsettlement materials

is accentuated by the presence of vertical tension cracks which are parallel with the bank. This tension crack development results from the relatively unweathered condition and hence isotropic nature of the postsettlement and young paleosol materials. Old paleosol materials have a well developed polygonal structure which controls stability. The seam materials between the polygonal blocks, have no cohesion, resulting in weakness planes separating individual blocks. Excessive seepage and pore water pressure leads to block failure. The failure rate is accentuated by the presence of easily eroded toe materials.

3. Bank instability is a three-stage process. Gravity-induced failure delivers slough to a bank toe position; secondly, the material is continuously disaggregated by weathering forces; and lastly, discrete particles are removed by fluid forces. In the study channels, this removal is rapid with little slough remaining in the failure location from one flow event to the next.

4. Bank stability analyses can be used to estimate the maximum height that the bank materials can support. They can also be used to estimate the slope for the worst case and thus recommend slopes flat enough to insure stability.

5. Bed failure by headcut movement is extremely complex. Knickpoints typically occur in old paleosol materials with a well-developed polygonal structure. Failure is initiated by a chute slowly eroding through the cohesive materials during low flow periods. This is accompanied by the removal of the weak seam materials. Individual blocks, thus isolated, roll to the chute and are moved downstream by high velocity flows. The initial chute formation and seam material removal is highly dependent upon low flow conditions.

6. These conclusions illustrate the complexity of channel failure processes and the difficulties involved in simulating such conditions in process-based models. Failure occurs in reaches of excessive energy expenditure typically associated with nonuniform flow. This necessitates use of three-dimensional simulation models for accurate representation of field conditions. Additionally, the type and rate of failure is affected by stratigraphic controls.

7. The distribution and properties of the valley-fill units (the units imposing stratigraphic controls) and their ^{14}C ages indicate

that formation of the dominant controls of these units was paleoclimatic and base level fluctuation. This finding enhances the predictive capabilities for extrapolating results from the study watershed to others subjected to similar late-Quaternary paleoclimatic and base level conditions. Similarly, these results illustrate the utility of the valley-fill stratigraphic record as a measure of paleoclimatic conditions.

8. The geologic studies have established that the presently-mapped stratigraphy is not accurate in the study area and probably is not accurate in a large part of North Mississippi. The surface of the Zilpha is disconformable, representing an erosional surface which we think has regional significance. Water is perched above this surface due to the relative impermeability of the Zilpha material. Additionally, the erosion surface is not congruent with surface watershed definition, resulting in groundwater transfer between watersheds. This greatly complicates water budget considerations inherent in the detailed Goodwin Creek study. Resistivity methods appear to have great utility for further defining the configuration of the disconformable Zilpha surface.

9. The uncertainty concerning the nature and distribution of the near-surface geologic units limits full development of capabilities for predicting properties of the valley-fill units. The geologic materials are source materials for the valley-fill deposits and both the source material availability and controlling erosive processes must be accurately defined for full development of predictive landscape models.

9.2.5.2 Recommendations:

1. Relations between valley-fill units, failure mechanisms, and failure rates should be quantified.

2. The landscape is a complex arrangement of land forms and land form elements, in a physical sense, but systematic and logical when defined on the basis of controlling processes. A complete understanding of the landscape, based on controlling processes, is essential in order to more efficiently manage the present pervasive environmental problems such as those associated with channel instability. It is hoped that such an understanding would lead to the development of

landscape models of sufficient detail to facilitate coupling with mathematical models. We believe that this coupling of models would:

a. simplify model input requirements,

b. maximize predictive capabilities with respect to time and space,

c. result in better definition of the basic processes underlying specific environmental problems.

3. In order to better understand the landscape, a prerequisite to landscape model development, the following land forms and land form properties should be better defined:

a. Loess - the ages of the loess, the nature of the contacts between individual loess units and the nature of the contact between loess and valley fill.

b. Valley terraces - the distribution and age.

c. Valley-fill deposits - comparable studies should be made east of the present study area to verify the valley-fill sequence and to establish the maximum depth of the Quaternary valley erosion. Studies should also be made west of the present study area to verify the valley-fill sequence and to establish the relation of these deposits with those in the Mississippi River Valley.

Geologic studies should be conducted to better define the materials overlying the Zilpha surface. Secular variation or other paleomagnetic determinations may be useful for dating layered clay bodies in this material. The possibility of a (buried) ancestral Mississippi River channel between the present study area and the Bluff line should be investigated.

4. Relations between soil map units and valley-fill deposits should be evaluated. If they are related, the soil map units could be used to infer the general nature of the subsurface deposits.

5. Analyses and charts of bank stability were based on log-spiral toe failure. Charts for other types of failure should be developed.

6. Routine procedures should be developed to analyze the failure surface in complex stratigraphic banks.

10 ACKNOWLEDGEMENTS

I wish to acknowledge the help, information, and data provided me by the staff and authors of the Appendices. Without their help, it would not have been possible to complete this project. I particularly want to thank Thelma Russell for many typings of the Comprehensive Report; Sandra Sanders who, by herself, typed this entire report including all 14 Appendices in a very short period of time; Henry Roy Smith, the draftsman, who prepared all the figures that went into this report and its 14 Appendices; and Winfred Cook who supervised the drafting and prepared all of the figures and photographs for publication. All of us wish to pay special recognition to all the technicians who put in many tiring weeks and months in the collection and analyses of data that went into this project. They are the ones responsible for the success of the project. Tommie Simpson, the Administrative Officer, and her staff did an excellent job keeping track of funds in the many accounts through which funding was dispersed. We also acknowledge the support given us by farmers in the area who have voluntarily donated rights-of-way and, in many cases, land for the construction of some of the research facilities.

I also wish to thank our National Program Staff, Dr. C. D. Ranney our Area Director, and Dr. Edgar H. Kendrick the Regional Administrator for their support in the conduct of this program. Staff members of both Mississippi State University, and the University of Mississippi are to be thanked for providing professional support.

Lastly, I want to acknowledge the financial support and motivation provided by Colonel Gerald E. Galloway, Colonel Samuel P. Collins, John E. Henley, Roy O. Smith, Ray Lucius, David S. Haworth, all of the Vicksburg District, Corps of Engineers. Without the funds they provided there would have been no project. We especially want to thank Brien Winkley, also of the Vicksburg District, for the many days he spent with us offering valuable suggestions and comments that helped make the project a successful one.

REFERENCES

Ackers, P. 1964. "Experiments on small streams in alluvium." J. Hyd. Div., ASCE, Proc. HY4, pp. 1-37.

Ackers, P. 1980. "Meandering Channels and the Influence of Bed Material," International Workshop on Engineering Problems in the Management of Gravel Bed Rivers. Newtown, Wales, U.K.

Alonso, C. V., Neibling, W. H., and Foster, G. R. 1980. "Estimating Sediment Transport Capacity in Watershed Modeling." Accepted for publication in Trans. ASAE, 1981.

ASCE Task Committee, 1971. "Sediment Transportation Mechanics:Sediment Discharge Formulas," Jour. of Hyd. Div., ASCE, Vol. 97, No. HY4, pp. 523-527.

ASCE Task Committee, 1975. "Sedimentation Engineering," Vito A. Vanoni Ed. Pub. by ASCE, N.Y. 745 pp.

ASCE, 1975. Symposium on Modeling Techniques, 2nd Annual Symposium of the Waterways and Harbors and Coastal Engineering Division of ASCE, San Francisco, CA (Two volumes) 1684 pp.

ASCE, 1976. Symposium on Inland Waterways for Navigation Flood Control and Water Division, 3rd Annual Symposium of the Waterways and Harbors and Coastal Engineering Division of ASCE, Colorado State University, Ft. Collins, CO (two volumes) 1971 pp.

Bagnold, R. A., 1960. "Some Aspects of River Meanders," U.S. Geol. Survey Prof. Paper 282-E, p. 1-10.

Barnes, H. H., Jr., 1967. "Roughness Characteristics of Natural Channels," U.S. Geol. Water Supply Paper 1849, 213 pp.

Bathurst, J. C., Thorne, C. R., and Hey, R. D., 1979. "Secondary Flow and Shear Stress at River Bends," Jour. of Hyd. Div., ASCE, Vol. 105, No. HY10, pp. 1277-1295.

Bennett, J. P., and Nordin, C. F., 1977. "Simulation of Sediment Transport and Armoring," Hydrological Sciences Bulletin, Vol. XXII, No. 4, pp. 555-569.

Bergman, D. L., and Sullivan, C. W., 1963. "Channel Changes on Sandstone Creek near Cheyenne, Oklahoma, Article 87, USGS Prof. Paper 475-C pp. C-145 thru C-148.

Borah, D. K., Prasad, S. N., and Alonso, C. V. 1980. "Kinematic Wave Routing Incorporating Shock Fitting," Water Resources Research, 16(2), pp. 529-541.

Bowie, A. J., 1980. "Channel Contribution to Sediment Yields in Complex Watersheds," Presented at ASAE Annual Meeting, San Antonio, TX, June 1980, ASAE Paper No. 80-2031.

Bradford, P. G., Farrell, D. A., and Parson, W. E., 1973. "Factors Affecting Gully Stability," Soil Science Society of America Proc. Vol. 37.

Bradley, J. N., and Peterka, A. J., 1957. "Hydraulic Design of Stilling Basins," Journal of the Hydraulics Division, ASCE, Vol. 83, No. HY5, Proc. Papers 1401, 1402, 1043, 1404, 1405, 1406.

Brooks, N. H., 1958. "Mechanics of Streams with Movable Beds of Fine Sand," Trans. ASCE, Vol. 123, pp.

California Dept. of Transportation, 1970. "Bank and Shore Protection in California Highway Practice," State of California Documents Section, Sacramento, CA, pp. 423.

Carson, M. A., and Kirkby, M. J., 1972. "Hillslope Form and Process," Cambridge, Univ. Press, U.K. 475 pp.

Charlton, F. G., 1980. "River Stabilization and Training in Gravel Rivers," International Workshop on Engineering Problems in Management of Gravel and Rivers, Newtown Wales, U.K.

Chen, Yung Hai, 1979. "Water and Sediment Routing in Rivers," Chapter 10 in Modeling of Rivers, edited by H. W. Shen, John Wiley and Sons, pp. 10.1-10.97.

Chow, Van Te., 1959. "Open Channel Hydraulics," McGraw Hill Book Co., New York, pp. 98-123.

Colby, Bruce R., 1964. "Discharge of Sands and Mean Velocity Relationships in Sand-Bed Streams," USGS Prof. Paper 462-A, Washington, D.C., 47 p.

Coleman, N. L., 1962. "Observations of Resistance Coefficients in a Natural Channel," Pub. No. 59, IASH Commission on Land Erosion, Bari, Italy, pp. 336-352.

Coleman, N. L., 1971. "Analyzing laboratory measurements of scour at Cylindrical Piers in Sand Beds," Proc. IAHR - XIV Congress, Paris, France, Vol. III.

Cory, A. T., 1949. "Influence of Shape Factor on the Fall Velocity of Sand Grains," M.S. Thesis, Colorado A and M College, 102 p.

Costello, W. R., 1974. "Development of Bed Configurations in Coarse Sands," Ph.D. Thesis, Mass. Inst. of Technology, Report 74-1, 120 pp.

Culbertson, D. M., Young, L. E., and Brice, J. C., 1967. "Scour and Fill in Alluvial Channels, "U.S.G.S. Open-File Report, 58 p.

Donnelly, Charles A., and Blaisdell, Fred W., 1954. "Straight Drop Spillway Stilling Basin," Technical Paper No. 15, Series B., St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

Donnelly, Charles A., and Blaisdell, Fred W., 1965. "Straight Drop Spillway Basin," ASCE, Vol. 91. No. HY3, Proc. Paper 4328, pp. 101-131.

Einstein, H. A., 1950. "The Bed-Load Function for Sediment Transportation in Open Channels," USDA SCS Technical Bulletin 1026, Washington, D.C., 71 p.

Einstein, H. A., 1971. "On Secondary Currents and Sediment Motion," Chapter 18 in River Mechanics, Editeu and Published by H. W. Shen, pp. 18.1-18.10.

Ethridge, L. T., 1979. "Photogrammetric interpretation of stream channel morphology, Johnson and Goodwin Creeks, Panola County, Mississippi," M.E.S. Project, Dept. of Geol., The University of Mississippi, University, MS 24 0.

Fisk, H. N., 1944. "Geological Investigations of the Alluvial Valley of the Lower Mississippi River," Mississippi River Comm., Vicksburg, MS. 78 p.

Fortier, S., and Scobey, F. C., 1926. "Permissible Canal Velocities," Trans. ASCE, Vol. 89, pp. 940-956.

Foster, G. R., and Meyer, L. D., 1975. "Mathematical Simulation of Upland Erosion by Fundamental Erosion Mechanics," In Present and Prospective Technology for Predicting Sediment Yield and Sources, Agricultural Research Service, ARS-S-40, pp. 190-207.

Gessler, J., 1967. "The Beginning of Bedload Movement of Mixtures Investigated as Natural Armoring in Channels," Transaction T-5, W. M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology.

Gessler, J., 1970. "Self-stabilizing Tendencies of Alluvial Channels," Jour. of the Waterways and Harbors Div., ASCE, Vol. 96, No. WW2, pp. 235-249.

Gifford, G. F., and Hawkins, R. H., 1978. "Hydrologic Impact of Grazing on Filtration:A Critical Review," Water Res. Res., Vol. 14, pp. 305-313.

Grissinger, E. H., Murphey, J. B., and Little, W. C., 1980. "Bank Erosion of Cohesive Materials," International Workshop on Engineering Problems in the Management of Gravel-Bed Rivers, Newtown, Wales, U.K.

Gupta, Avigil, 1975. "Stream Characteristics in Eastern Jamaica:An Environment of Seasonal Flow and Large Floods," Am. J. Sci., Vol. 275, pp. 825-847.

Guy, H. P., 1974. "An Overview of Urban Sedimentology," Proc. National Symposium on Urban Rainfall and Runoff and Sediment Control, Univ. of KY.

Harmon, W. C., and Meyer, L. D., 1978. "Cover, Slope and Rain Intensity Affect Interrill Erosion," Proc. MS Water Res. Conf., Miss. State Univ., Miss. State, MS, pp. 9-16.

Harrison, A. S., 1950. "Report on Special Investigations of Bed Sediment Segregation in a Degrading Bed," Report Series No. 33, Univ. of CA, Institute of Engineering Research, Issue No. 1, Berkeley.

Hickin, E. J., and Nanson, C. L., 1975. "The Character of Channel Migration on the Beaton River, Northwest British Columbia," Geol. Soc. Amer. Bull. Vol. 86, pp. 487-494.

Hickin, E. J., 1978. "Mean Flow Structure in Meanders of the Squamish River, British Columbia," Canadian Jour. Earth Science, Vol. 15, pp. 1833-1849.

Kellerhals, R., 1980. "River Regulation and Channel Stability," International Workshop on Engineering Problems in the Management of Gravel Bed Rivers, Newtown, Wales, U.K.

Kennedy, J. F., 1961. "Stationary Wave and Antidunes in Alluvial Channels," Report KH-R-2, California Institute of Technology, Pasadena, CA, 146 p.

Keown, M. P., Oswalt, N. R. Perry, E. B., Dordeau, E. A., Jr., 1977. "Literature Survey and Preliminary Evaluation of Streambank Protection Methods," Tech. Report H-77-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kerssens, P. J. M., Van Rign, L. C. and Van Wijngaarden, J. J., 1977. "Model for Non-Steady Suspended Sediment Transport," Proc. Seventeenth Congress of the International Association for Hydraulic Research, Vol. 1, pp. 113-120.

Keulegan, G. H., 1938. "Laws of Turbulent Flow in Rough Channels," U.S. Dept. of Commerce, National Bureau of Standards Research Paper No. 1151, Jour. of Research of NBS, Vol. 21, pp. 707-741.

Lacey, G., 1930. "Stable Channels in Alluvium," Inst. Civil Engr., Proc., Vol. 229, pp. 259-284.

Lane, E. W., 1953. "Design of Stable Channels," Trans. ASCE, Vol. 120, pp. 1234-1260.

Lane, E. V., 1957. "A Study of the Shape of Channels formed by natural streams flowing in erodible material," MRD Sediment Series No. 9, US Army Engineering Div., Missouri River, Corps of Engineers, Omaha, Neb.

Lane, E. W., and Carlson, E. J., 1953. "Some Factors Affecting the Stability of Canals Constructed in Coarse Granular Materials," Proc., IAHR-ASCE International Hydraulics Convention, Minneapolis, Minn. pp. 37-48.

Langbein, W. B., and Leopold, L. B., 1966. "River Meanders - Theory of Minimum Variance," U.S. Geo. Survey Prof. Paper 422-H, 15 pp.

Laursen, E. M., 1952. "Observations on the Nature of Scour," Proc. 5th Hyd. Conf. Bull. 34, Univ. of Iowa Studies in Engineering, Iowa City, Iowa.

Laursen, E. M., 1960. "Scour of Bridge Crossings," Journal Hyd. Div., ASCE, Vol. 89, No. HY2, pp. 39-54.

Laursen, E. M., 1963. "An Analysis of relief bridge scour," Jour. Hyd. Div., ASCE, Vol. 89, No. HY3, pp. 93-118.

Lee, B. N., and Lobson, H. E., 1974. "Stochastic Analysis of Dune Bed Profiles," Jour. Hydr. Div., ASCE, Vol. 100, No. HY7, pp. 849-867.

Leopold, L. B., Wolman, M. G., and Miller, J. P., 1964. "Fluvial Processes in Geomorphology," W. F. Freeman & Co., 522 p.

Leopold, L. B., and Maddock, T., Jr., 1953. "The Hydraulic Geometry of Stream Channels and Some Physiographic Implications," USGS Prof. Paper 242, 57 p.

Leopold, L. B., and Wolman, M. G., 1957. "River Channel Patterns:Braided, Meandering and Straight," USGS Prof. Paper 282-B, pp. 39-85.

Leopold, L. B., and Wolman, M. G., 1960. "River Meander," Geol. Soc. Amer. Bull., Vol. 71, p. 769-794.

Li, Ruh Ming, 1979. "Water and Sediment Routing from Watersheds," Chapter 9 in Modeling of Rivers, Edited by H. W. Shen, John Wiley & Sons, pp. 9.1-9.88.

Limerinos, J. T., 1970. "Determination of the Manning Coefficient from Measured Bed Roughness in Natural Channels," USGS Water Supply Paper 1898-B, 47 p.

Little, W. C., Mayer, P. G., 1972. "The Role of Sediment Gradation on Channel Armoring," Report ERC-0672, School of Civil Engineering, Georgia Institute of Technology.

Livesey, R. H., 1965. "Channel Armoring below Fort Randall Dam," Proc. 1965 Federal Interagency Sedimentation Conf., Misc. Pub. No. 970, USDA-ARS, 1963, pp. 461-470.

Lohnes, R. A., and Handy, R. L., 1968. "Slope Angles in Friable Loess," Jour. of Geology 76, p. 247-258.

Martin, J., 1976. "Principles of Data Base Management," Prentice-Hall, pp. ____________.

Megahan, W. F., 1975. "Sedimentation in Relation to Logging Activities in the Mountains of Central Idaho," In Present and Prospective Technology for Predicting Sediment Yield and Sources, ARS-S-40, pp. 24-82.

Meyer, L. D., 1974. "An Overview of the Urban Erosion and Sedimentation Processes," Proc. of National Symposium on Urban Rainfall and Runoff and Sediment Control, Univ. of KY.

Meyer, L. D., Foster, G. R., and Römkens, M. J. M., 1975. "Source of Soil Eroded by Water from Upland Slopes," In Present and Prospective Technology for Predicting Sediment Yield and Sources, ARS-S-40, pp. 177-189.

Morganstern, N. R., and Price, V. E., 1965. "The Analysis of the Stability of General Slip Surfaces," Geotechnique, pp. 79-93.

Moots, E. E., 1938. "A Study in Flood Waves," Univ. of Iowa. Studies in Engineering, Bulletin 14, 24 pp.

Neill, C. R., 1973. "Guide to Bridge Hydraulics," Road and Transportation Assoc. of Canada, Univ. of Toronto Press.

Nikuradse, J., 1933. "Laws of Flow in Rough Pipes," National Advisory Committee for Aeronautics, Tech. Memo. 1272. Translation of Stroemungsgesetze in rainen Rehren-Verein Deutch Engenieurs-Forchungsheft 351. Beilage in "Forsching auf den Gebriete des Ingenieurwesens" Ausgahe B, Bund 4, 1933, 62 pp.

Parker, G., 1979. "Hydraulic Geometry of Active Gravel River," Jour. Hyd. Div., Proc. ASCE, Vol. 103, HY9, Proc. Paper 14841, pp. 1185-1201.

Parker, G., and Peterson, A. W., 1980. "Bar Resistance of Gravel-Bed Streams," Jour. Hyd. Div., ASCE, Vol. 106, HY10, 16 pp.

Peterka, A. J., 1964. "Hydraulic Design of Stilling Basins and Energy Dissipators," Engineering Monograph No. 25, Bur. of Reclam., U.S. Dept. of Interior, Denver, CO.

Piest, R. F., Bradford, J. M., and Spomer, R. G., 1975. "Mechanisms of Erosion and Sediment Movement," In Present and Prospective Technology for Predicting Sediment Yield and Sources, Agricultural Research Service, ARS-S-40, pp. 162-176.

Prasad, S. N., and Alonso, C. V., 1976. "Integral-Equation Analysis of Flows over Eroding Beds," Proc. of ASCE Symposium on Inland Waterways for Navigation, Flood Control and Water Diversions, Vol. 1, Colorado State Univ., pp. 760-772.

Ritchie, J. T., 1972. "A Model for Predicting Evaporation from a Row Crop with Incomplete Cover," Water Res. Res. 8(5), 1204-1213.

Sarma, S. K., 1979. "Stability Analysis of Embankments and Slope," Jour. Geotechnical and Engineering Div., Proc. ASCE, Vol. 105, GT12, Proc. Paper 15068, pp. 1511-1523.

Saucier, R. T., 1974. "Quaternary Geology of the Lower Mississippi Valley," Research Series No. 6, Arkansas Archeological Survey, Fayetteville, 26 p.

Schumm, S. A., 1973. "Geomorphic Thresholds and the Complex Response of Drainage Systems," In Fluvial Geomorphology by Marie Morisawa (Editor). Publications in Geomorphology, State Univ. of New York, Binghamton, pp. 299-310.

Schumm, S. A., 1977. "The Fluvial Systems," John Wiley & Sons, 338 p.

Shen, H. W., 1979. "Modeling of Rivers," John Wiley & Sons, 20 Chapters.

Shulits, Sam, and Hill, R. D., Jr., 1968. "Bedload Formulas," Hydraulics Laboratory Bulletin, PA State Univ., Dec. 1968, pp. Part B - 153 p.

Simons, D. B., and Richardson, E. V., 1962-A. "Resistance to Flow in Alluvial Channels," Am. Soc. of Civil Engr. Trans., Vol. 127, pp. 927-1006.

Simons, D. B., and Richardson, E. V., 1962-B. "The Effect of Bed Roughness on Depth Discharge Relations in Alluvial Channels," USGS Water Supply Paper 1498-E, 226 pp.

Simons, D. B., Richardson, E. V., and Nordin, C. F., 1965. "Bedload Equation for Ripples and Dunes," USGS Prof. Paper 462-H, 9 p.

Simons, D. B., and Richardson, E. V., 1966. "Resistance to Flow in Alluvial Channels," USGS Prof. Paper 422-J, 61 p.

Simons, D. B., and Sentürk, F., 1976. "Sediment Transport Technology," Water Resources Publication, Ft. Collins, CO.

Simons, D. B., 1979. "River and Canal Morphology," Chapter 5 in Modeling of Rivers, Edited by H. W. Shen, John Wiley & Sons, pp. 5.1 - 5.81.

Simons, D. B., and Li, R. M., 1979. "Analysis of Watersheds and River Systems," Chapter 11 in Modeling of Rivers, Edited by H. W. Shen, John Wiley & Sons, pp. 11.1 - 11.58.

Smith, R. E., and Parlange, J. Y., 1978. "A Parameter-Efficient Hydrologic Infiltration Model," Water Resources Research, Vol. 14, No. 3, pp. 533-538.

Smith, R. E., Chery, D. L., Jr., Renard, K. G., and Gwinn, W. R., 1981. "Supercritical Flow Flumes for Measurement of Sediment Laden Flow," USDA Technical Bulletin No. ____, USDA-SEA, 1981.

Soil Conservation Society of America, 1977. "Soil Erosion:Prediction and Control," Published by Soil Conservation Society of America, pp. 393.

Stein, R. A., 1965. "Laboratory Studies of Total Bed and Apparent Bed Load," Jour. Geophysical Research, Vol. 70, No. 8, pp. 1831-1842.

Stevens, M. A., Simons, D. B., and Richardson, E. V., 1975. "Non-Equilibrium River Form," Jour. Hyd. Div., ASCE, Vol. 101, pp. 557-566.

Taylor, D. W., 1948. "Fundamentals of Soil Mechanics," John Wiley & Sons, New York. p.________.

Teryaghi, K., and Peck, R. B., 1948. "Soil Mechanics and Engineering Practices," John Wiley & Sons, N.Y., 727 pp.

Thomas, W. A., 1980. "Calculation of Sediment Movement in Gravel Bed Rivers," Proc. Workshop on Engineering Problems on the Management of Gravel Bed Rivers, Newtown Wales, U.K.

Thorne, C. R., 1980. "Processes and Mechanisms of River Bank Erosion," International Workshop on Engineering Problems in the Management of Gravel Bed Rivers, Newtown, Wales, U.K.

Thorne, C. R., Alonso, C. V., and Bathurst, J. C., 1980. "Discussion of Hydraulic Geometry of Active Gravel Rivers," by G. Parker, Jour. of Hydr. Div., ASCE, Vol. 106, No. HY7, pp. 1269-1271.

Thorne, C. R., and Tovey, N. K., 1981. "Stability of Composite River Banks," Earth Surface Processes and Land Forms (In Press).

US Army Corps of Engineers, 1969. "A Study of Streambank Erosion in the United States, August 1967," Report of the Chief of Engineers to the Secretary of the Army.

US Army Corps of Engineers, 1978. "Interim Report to Congress," Section 32 Program, Streambank Erosion Control Evaluation and Demonstration Act of 1974.

USDA Science and Education Administration, 1980. "CREAMS, A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems," Conservation Research Report 26, 643.

USDA, Soil Conservation Service, 1963. "Soil Survey, Panola County, MS," Series 1960, No. 10, USDA, SCS in cooperaton with MS Ag. Exp. Station, 63 pp plus 122 plates.

USDA, Soil Conservation Service, 1972. "National Engineering Handbook," Hydrology Section 4, Chapter 4 - 10.

USDA, Soil Conservation Service, Engineering Division, 1976. "Hydraulic Design of Riprap Gradient Control Structures," Technical Release No. 59.

US Geological Survey, 1955. "Flood of May 27-28, 1954, in Panola and Lafayette Counties, MS," Water Resources Div., Jackson District, US Geological Survey, 13 pp.

Vanoni, Vito A., 1946. "Transportation of Suspended Sediment in Water," Trans. ASCE, Vol. III, pp. 67-133.

Vestal, F. E., 1956. "Panola County Geology Bulletin 81," MS State Geology Survey, Jackson, MS, 157 pp.

Williams, J. R., and Berndt, H. D., 1977. "Sediment Yield Prediction Based on Watershed Hydrology," Trans. ASAE 20(6) 1100-1104.

Williams, J. R., and Nicks, A. D., 1980. "SWRRB, A Simulator for Water Resources in Rural Basins," Unpublished.

Willis, J. C., and Coleman, N. L., 1969. "Unification of Data on Sediment Transport in Flumes by Similitude Principles," Water Resources Research, Vol. 5, No. 6, pp. 1330-1336.

Willis, J. C., and Kennedy, J. F., 1977. "Sediment Discharge of Alluvial Streams Calculated from Bed-Form Statistics," Iowa Institute of Hydraulic Research Report No. 202, June 1977, 200 p.

Winkley, B. R., 1980. "A Rivers Response of Man's and Nature's Activities," International Workshop on Engineering Problems in the Management of Gravel Bed Rivers, Newtown, Wales, U.K.

Wolman, M. G., and Leopold, L. B., 1957. "River Flood Plains:Some Observations on Their Formation," USGS Prof. Paper 282-C, pp. 87-109.

Wolman, M. G., and Brush, L. M., Jr., 1961. "Factors Controlling the Size and Shape of Stream Channels in Coarse Noncohesive Sands," USGS Prof. Paper 282-G, pp. 183-210.

Wylie, K. F., Alonso, C. V., Coleman, N. L., and Darden, R., 1977. "Some Stochastic Properties of Turbulent Tractive Forces in Open-Channel Flows," Proc. Fifth Biennial Symposium on Turbulence, University of Missouri-Rolla, pp. 181-189.

Yen, B. C., 1975. "Spiral Motion and Erosion in Meanders," Proc. 16th Congress, I.A.H.R., Sao Paulo, Brazil, Vol. 2, pp. 338-346.